RF Systems for the 3rd Generation Synchrotron Radiation Facilities

Lecture 14

Storage Ring

March 04, 2003

APS Bunch Length

RG1

Macro-pulse 40 ns

Micro-pulse (RMS) 5-8 ps

1.5 A, 250 pC

RG2

Macro-pulse 10 ns

Micro-pulse (RMS) 5-8 ps

1.5 A, 250 pC

PCG

Micro-pulse (FWHM) 2-7 ps

0.2nC - 0.7nC

150 A Peak

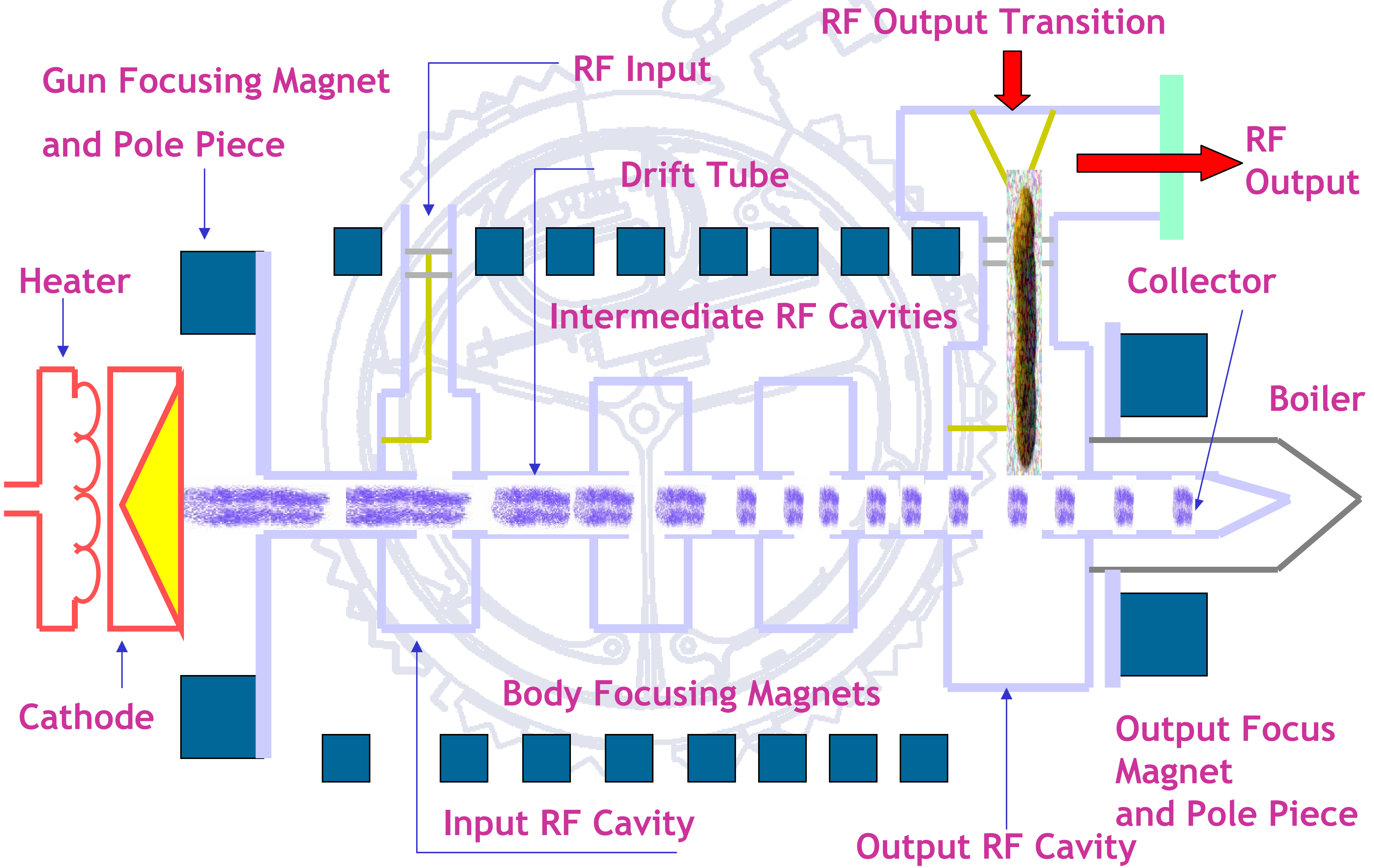
Linac 1 - 24 Pulses

PAR- FUND 0.92 nS(RMS),1-8 mA, 3.5nC

PAR- HARM 0.3 nS (RMS), 1-8 mA, 3.5nC

Booster 73ps (RMS), 1-7 nC, 1-8 mA

SR 35-100ps (2σ), 1-7 nC, 0.2-15 mA (single), 100 mA Bunch Train

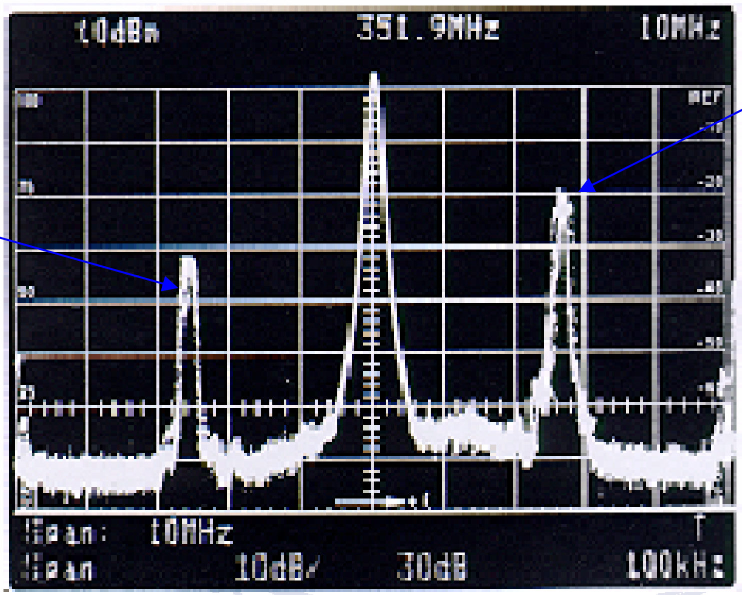


RF Output Transition
Gun Focusing Magnet
and Pole Piece
RF Input
Drift Tube
RF
Output
Heater
Intermediate RF Cavities
Collector
Boiler
Cathode
Body Focusing Magnets
Output Focus
Magnet
and Pole Piece
Input RF Cavity
Output RF Cavity

As a result of back streaming towards the gun area, electron bunches generate amplitude modulated sidebands on both sides of the rf output carrier and can also cause excessive mod anode current.

The modulation sidebands produced by the back-streaming electrons are usually present within ± 5 MHz of the carrier, and can be as high as -10dBc.

Lower Sideband



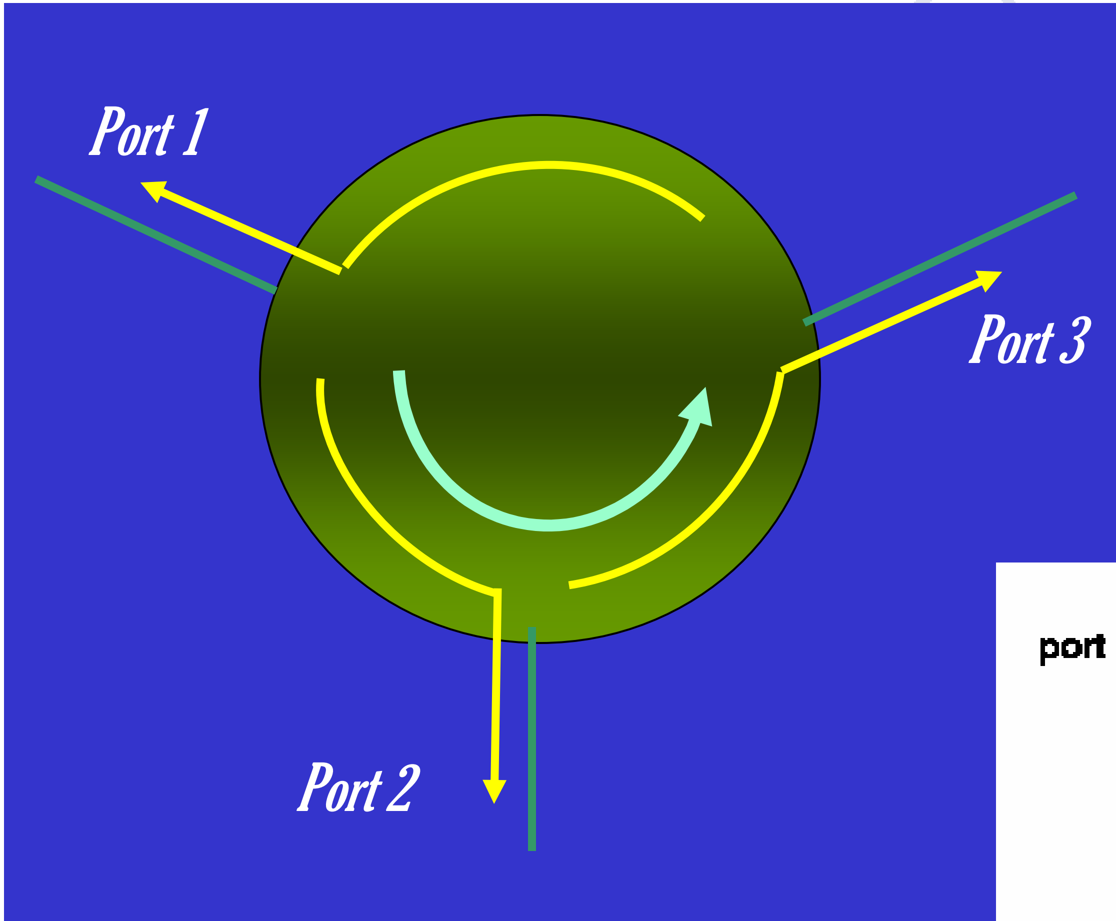
Upper Sideband

Cures:

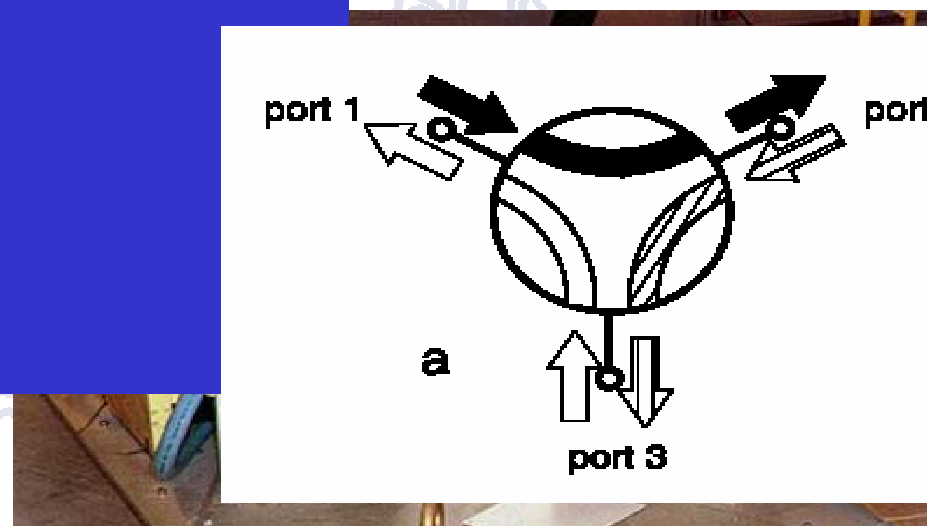
- Cavity re-tuning
- Change in the cathode voltage
- Change in the output load phase angle

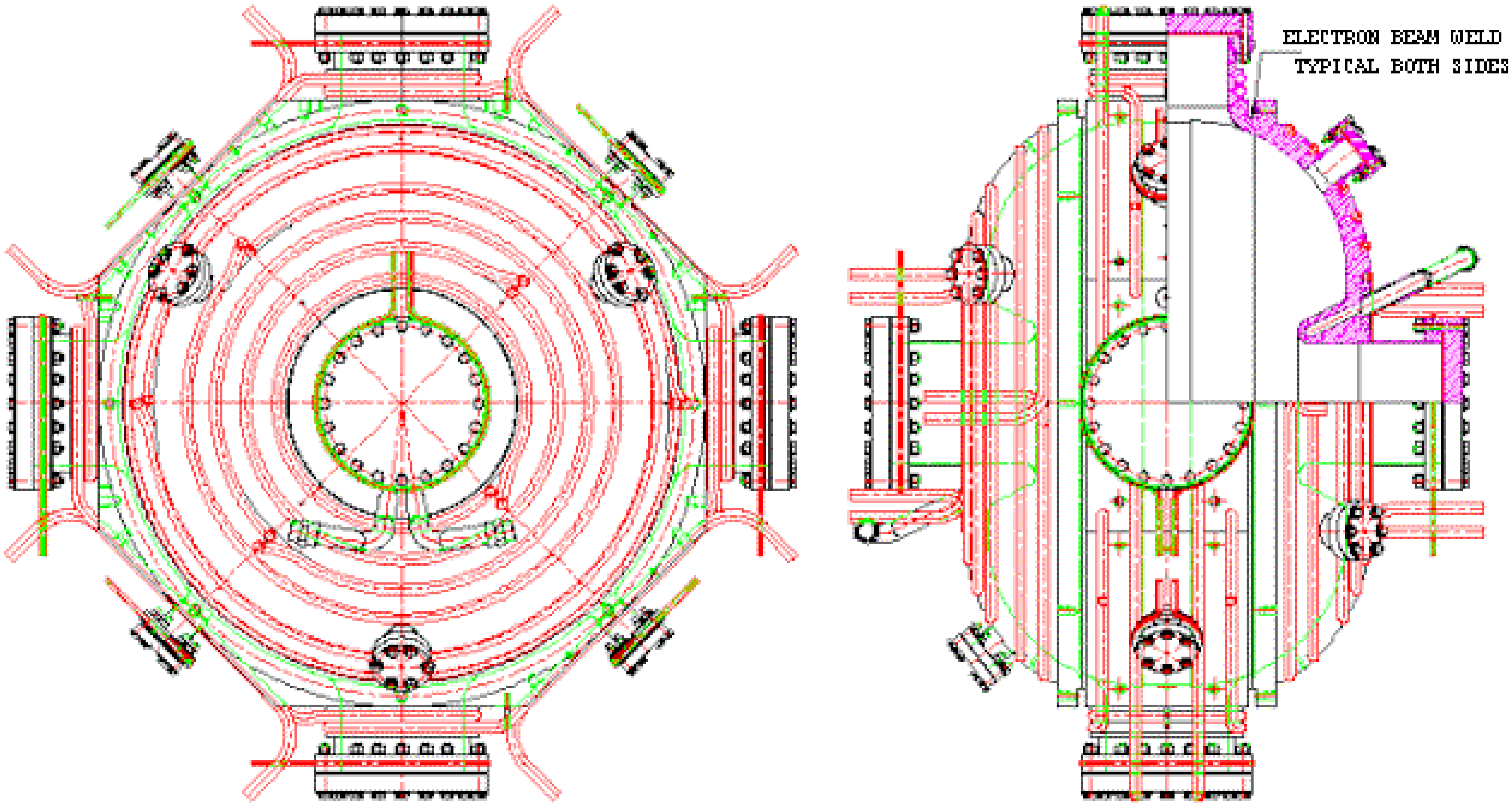
Klystron Sidebands

Circulator/ISOLATOR

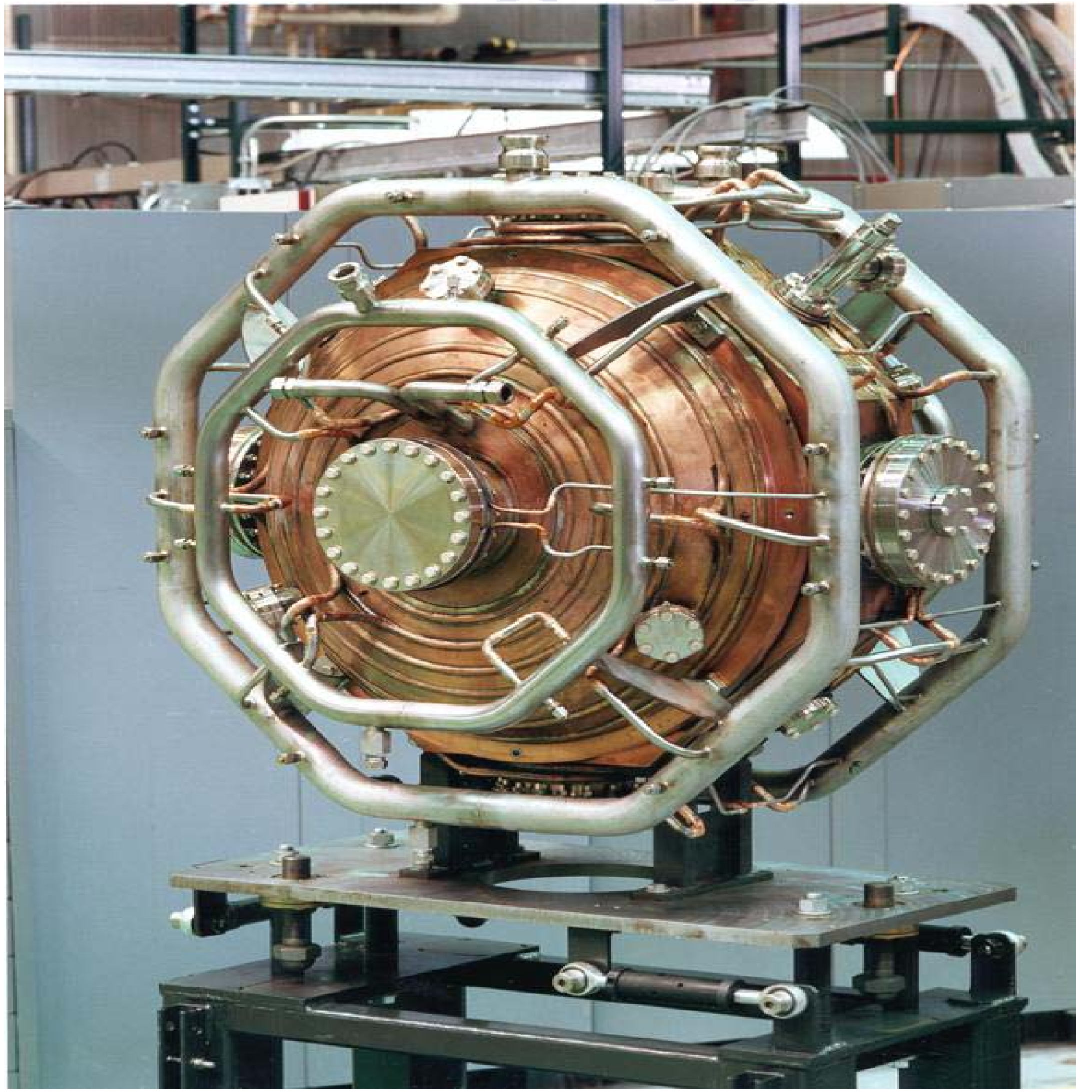


A microwave circulator is a nonreciprocal ferrite device which contains three or more ports. The input from port n will come out at port n +1 but not out at any other port. A three-port ferrite junction circulator, usually called the Y-junction circulator, is most commonly used.



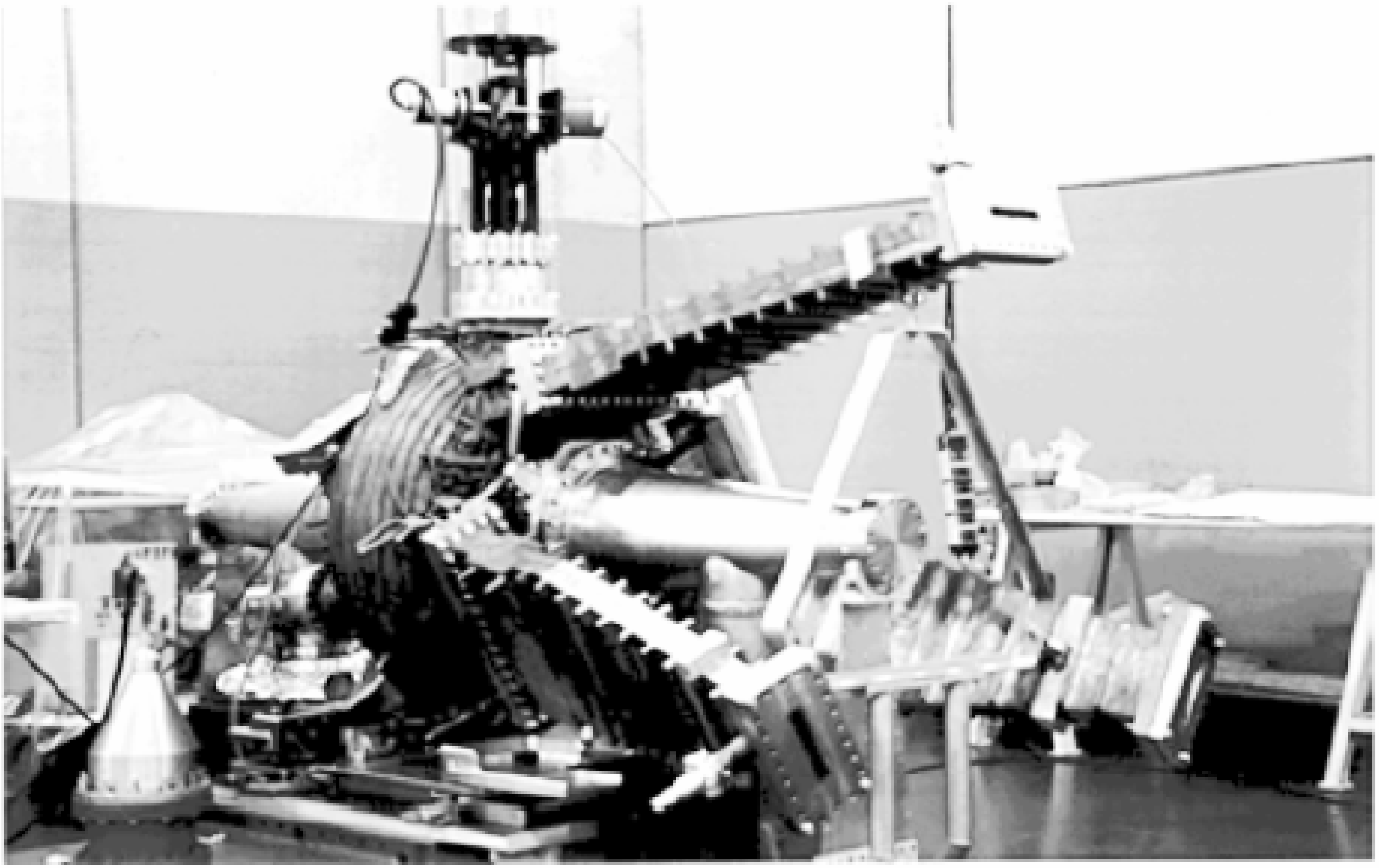


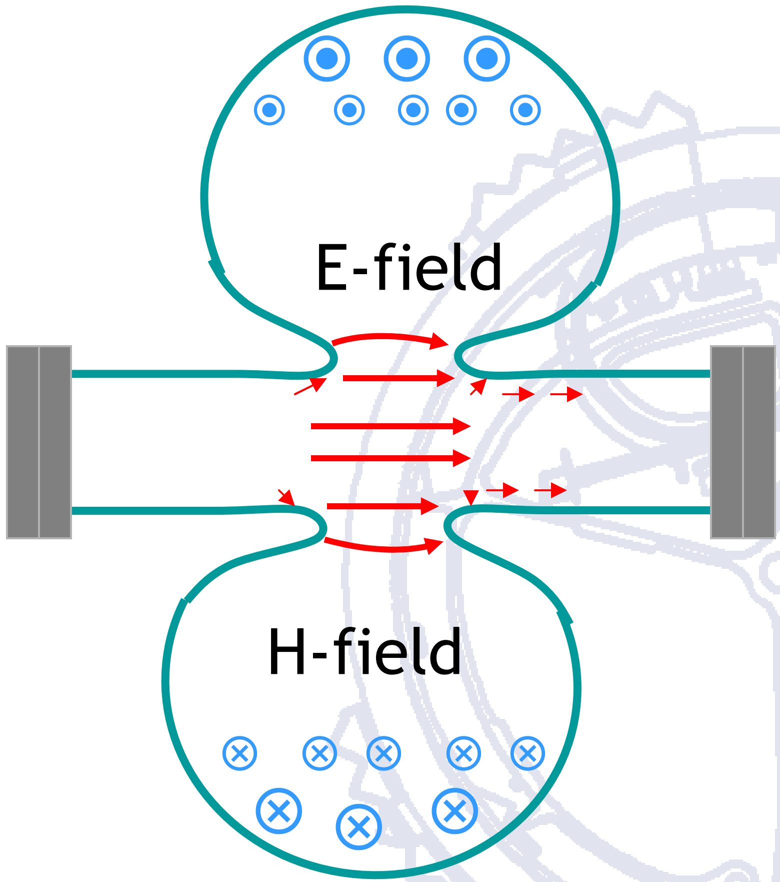
352 MHz Single Cell Nose-Cone SR RF Cavity



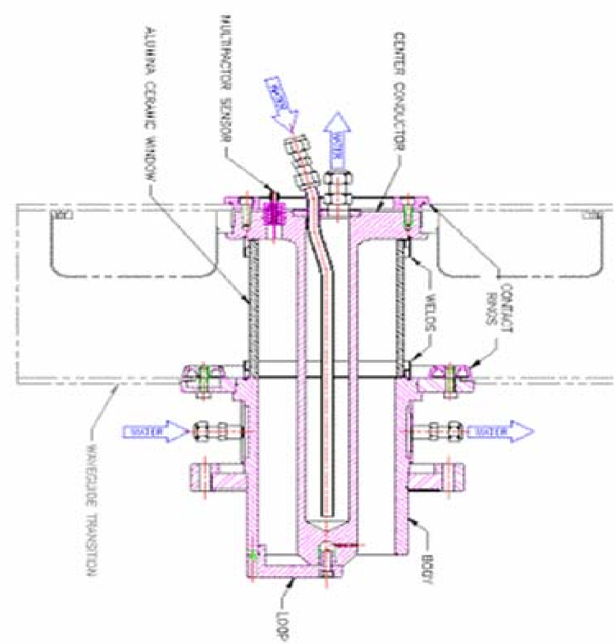
352 MHz Single Cell Nose-Cone SR RF Cavity

DAΦNE 368 MHz RF Cavity





Single Cell 352 Cavity



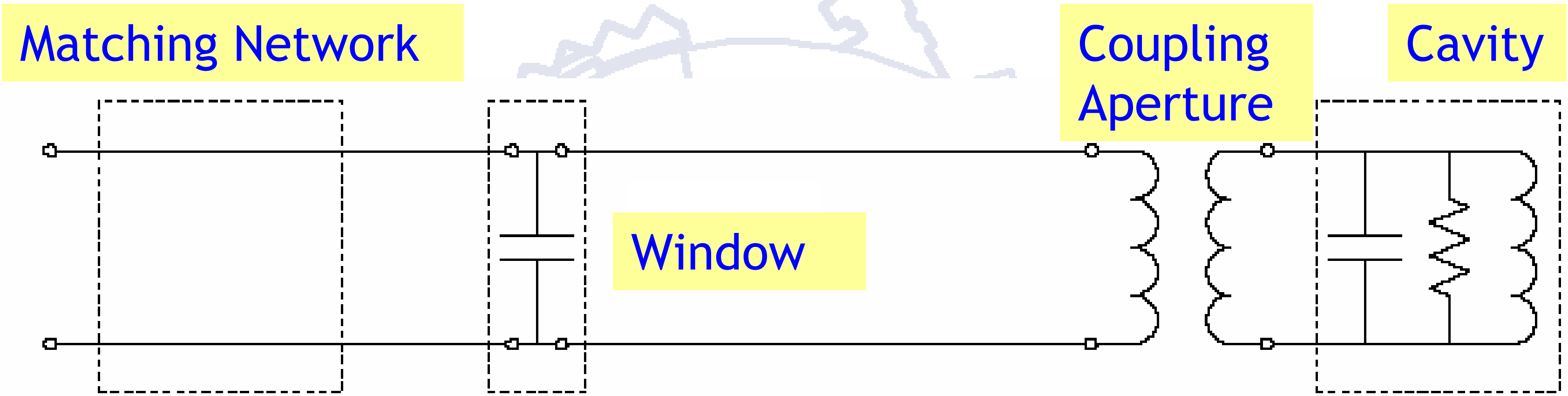
Power Coupler:

- To transfer power to the cavity through a dielectric window (air to vacuum barrier
- Coupling determines Q_{ext} of the cavity
- Need low RF reflection and transmission losses with beam loaded cavity
- Mechanical stability and Alignment
- Arcing and multipacting
- High vacuum seal
- Good mechanical strength thermal conductivity
- Low RF loss

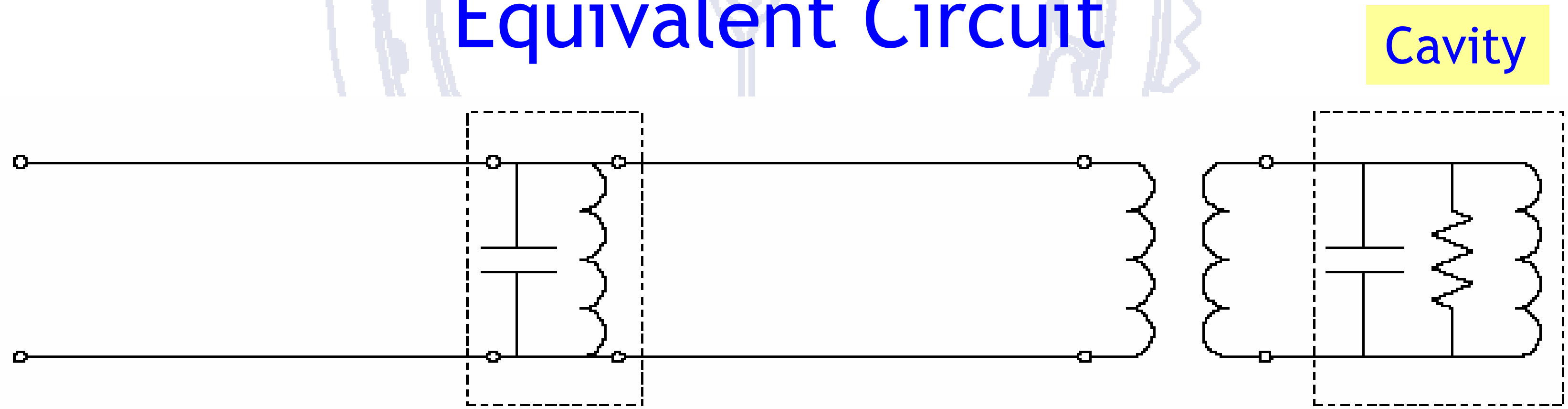
Coupler Design Requirements:

- RF frequency, peak and average power, cavity design
- RF matching and adjustment
- Waveguide type or coaxial line coupling
- Heat load and cooling
- Selection of window material – Purity and domains
- Coupler conditioning
- Secondary field emission and surface Ti coating
- RF breakdown, Joules heating and copper coating
- Fixed coupling. Variable coupling??

Coupler Equivalent Circuit:



Equivalent Circuit



Resonant Matching

Ceramic Window Matching:

- A thin ceramic window in a transmission line alone has a significant return loss (~-5dB to -10dB) due to its shunt capacitive loading.

  - *Return loss of a 0.015λ thick, 95% Alumina window in a 0.25 λ diameter 50 Ω coaxial transmission line is about -8dB*

- Tuning out the capacitive loading is required to ensure good RF power transmission.

- Tuning and matching can be done either locally or globally. Local tuning is more desirable to eliminate resonant standing wave formation in the transmission line.

Windows for Couplers:

Window shape

- Circular or rectangular disks for hollow waveguides
- Annular disk type for coaxial lines
- Circularly cylindrical window in waveguide transition
- Tapered cone
- Half wavelength thick (l/2)

Impedance matching

- Resonant cavity
- Resonant window
- Choke type inductive loading
- Tapered cone
- Half wavelength thick (l/2)

RF Coupling

To achieve zero reflected power in cavities with full beam loading, the RF system should fulfill the following conditions:

a. the reactive component of the beam current should be canceled by properly detuning the cavity so that the beam-loaded cavity is seen as a pure resistance;

b. this equivalent resistance is matched to the RF source impedance by the correct setting of the coupling factor.

The detuning Δf_m and the coupling factor β_m satisfying the conditions a) and b) are given by

$$\Delta f_m = \frac{f_{RF}}{2Q_\circ} \frac{P_b}{P_W} \cot \phi_s$$

$$\beta_m = 1 + \frac{P_b}{P_W}$$

$$\beta = \frac{Q_\circ}{Q_L} - 1$$

RF Coupling

The input coupler must be capable of feeding into the cavity a CW RF power of at least 150 kW (forward) and also to handle the full reflection.

It is of the coaxial type, terminated by a coupling loop. The coupling coefficient *m* b shall be adjustable within a range of 1 to 3.5 in order to match different beam loading conditions.

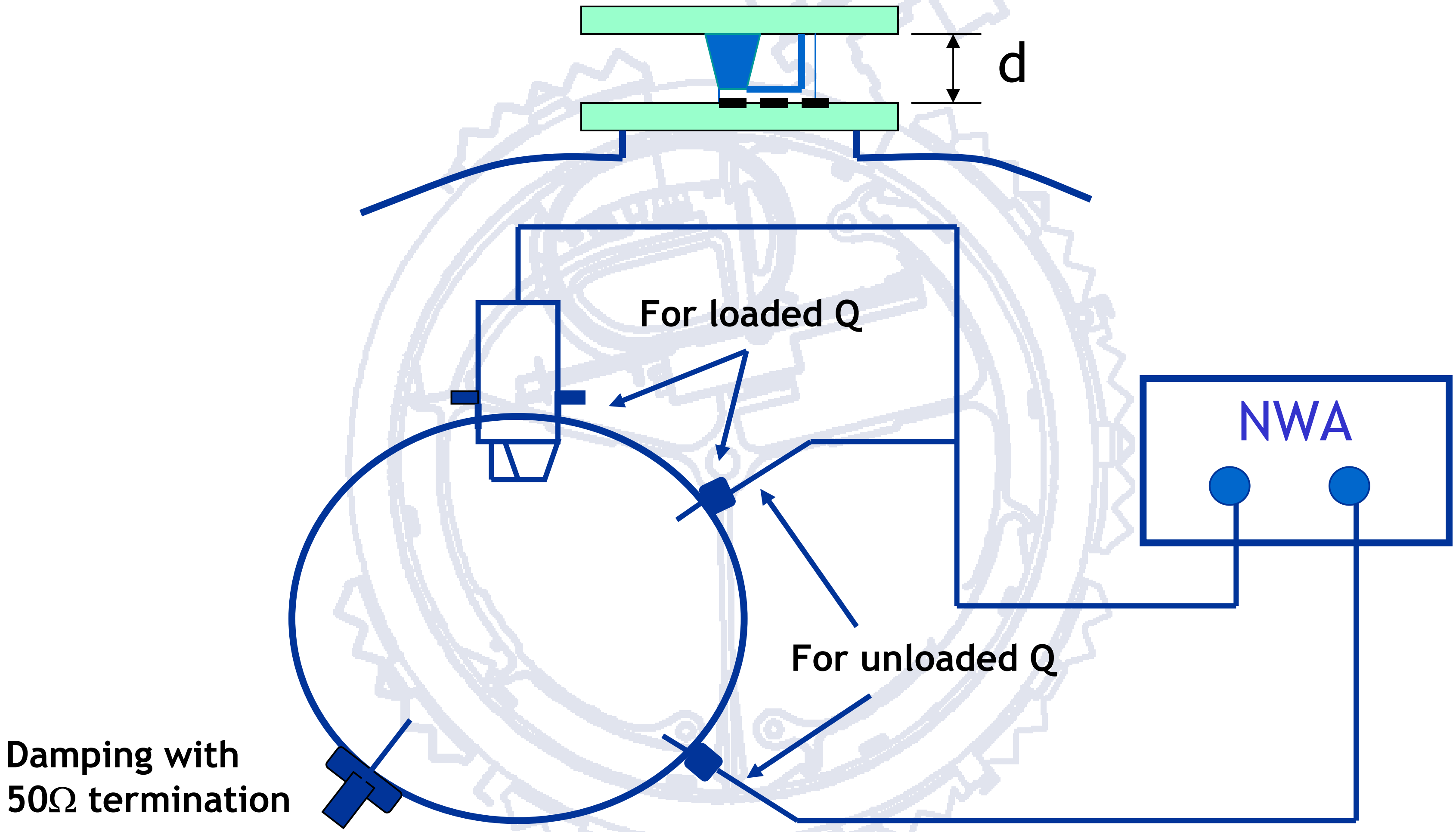
The RF requirements as well as the beam parameters are in strong dependence of the beam

RF Coupling

A coupling coefficient is defined as $\beta = \frac{Q_{\circ}}{Q_L} - 1$ where Q_0 is the unloaded Q and Q_L is the loaded quality factor.

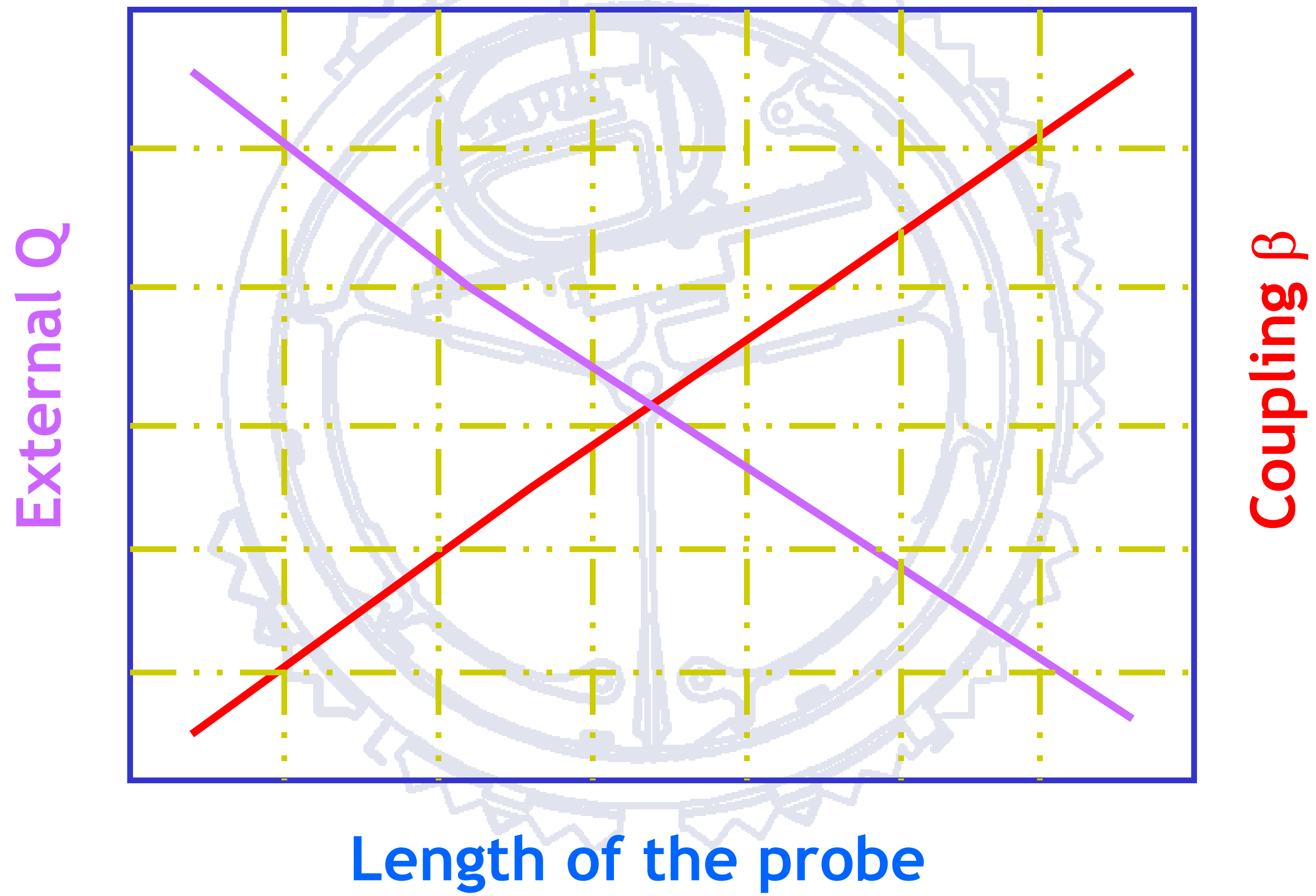
Depending on the extent of deQing of the fundamental mode in the single-cell cavity, the input coupler is positioned further in or out of the cavity accordingly to achieve matching at 50 . Damping the cavity simulates the beam loading when the beam passes through the single-cell cavities.

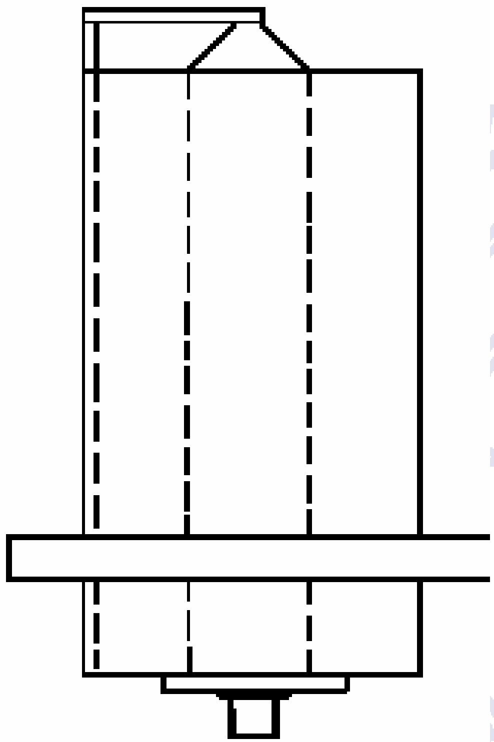
RF Coupling



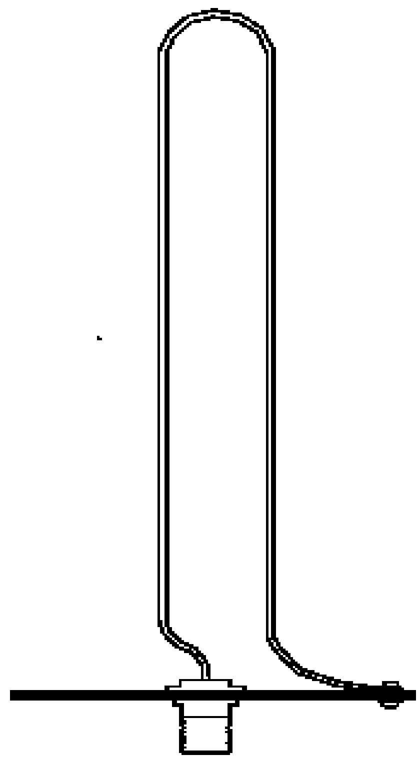
Coupling Measurement Setup

Cavity Coupling

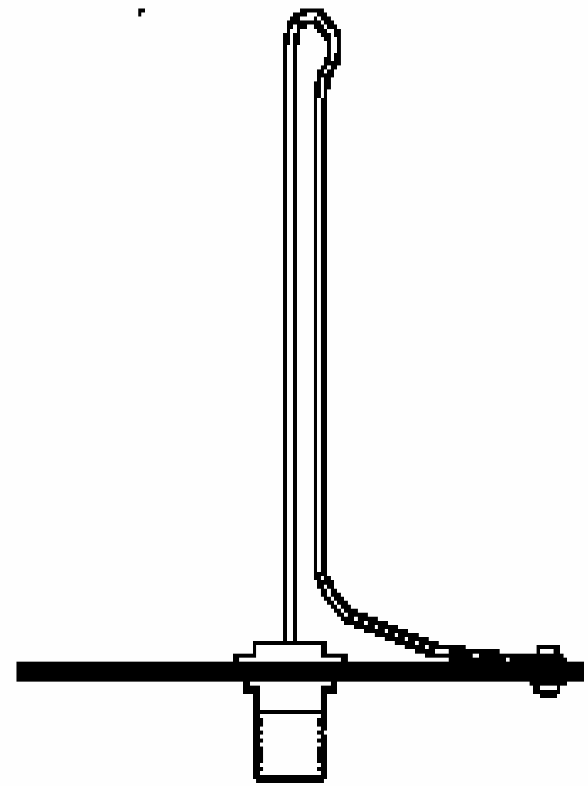




Input Coupler



Damper

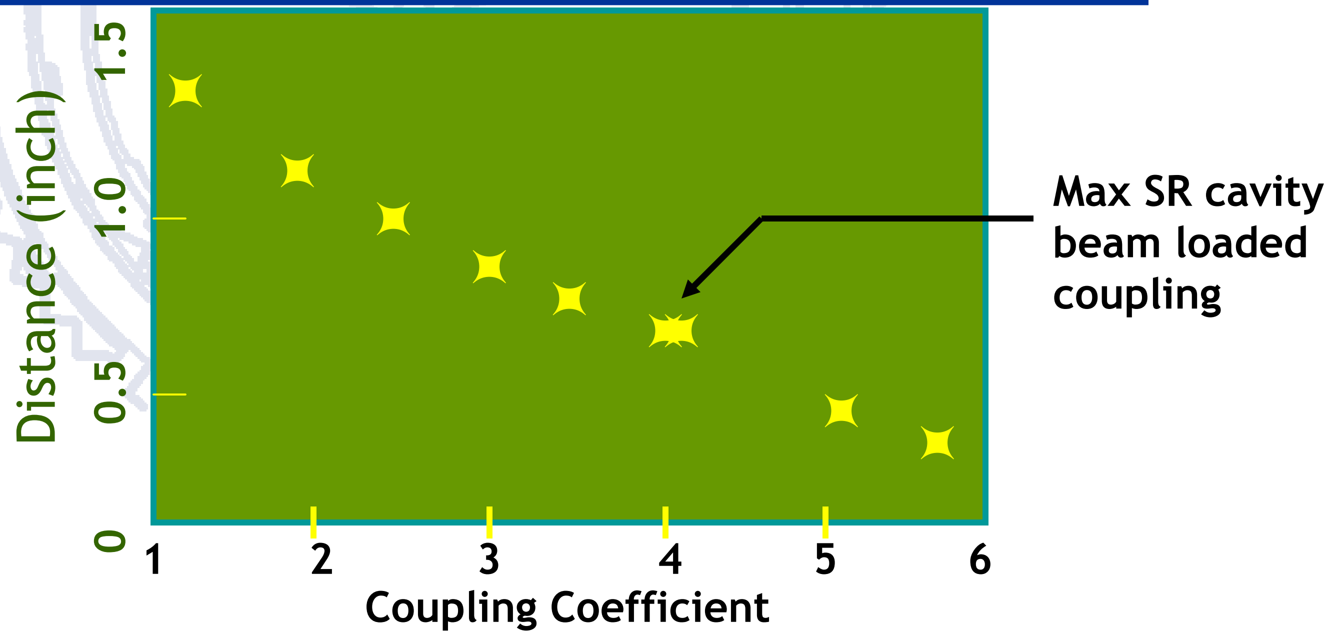


Field Probe

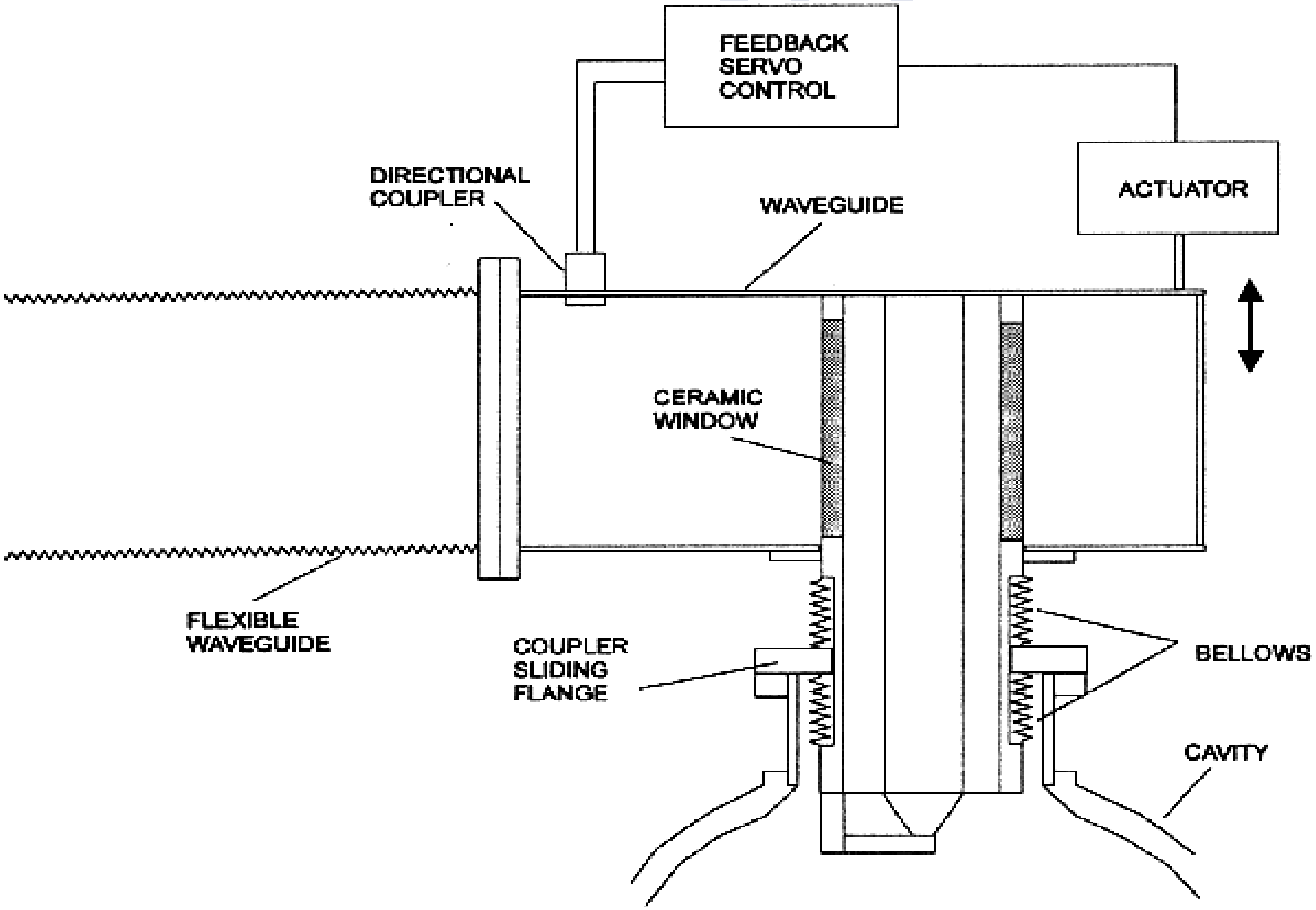
RF Coupling

Test Measurement Results:

Frequency	Impedance (S_{11})	Q	Coupling Coefficient	d
352.27	49.87-j1.5	9450	1.116	1.3
352.31	49.9+j0.10	6950	1.878	1.0
352.33	49.1+j0.82	5900	2.390	0.8
352.30	50.5+j0.90	5300	2.774	0.72
352.27	50.08+j0.2	4000	4.00	0.50
352.32	49.8+j0.3	3000	5.667	0.20



Variable Input Coupler:



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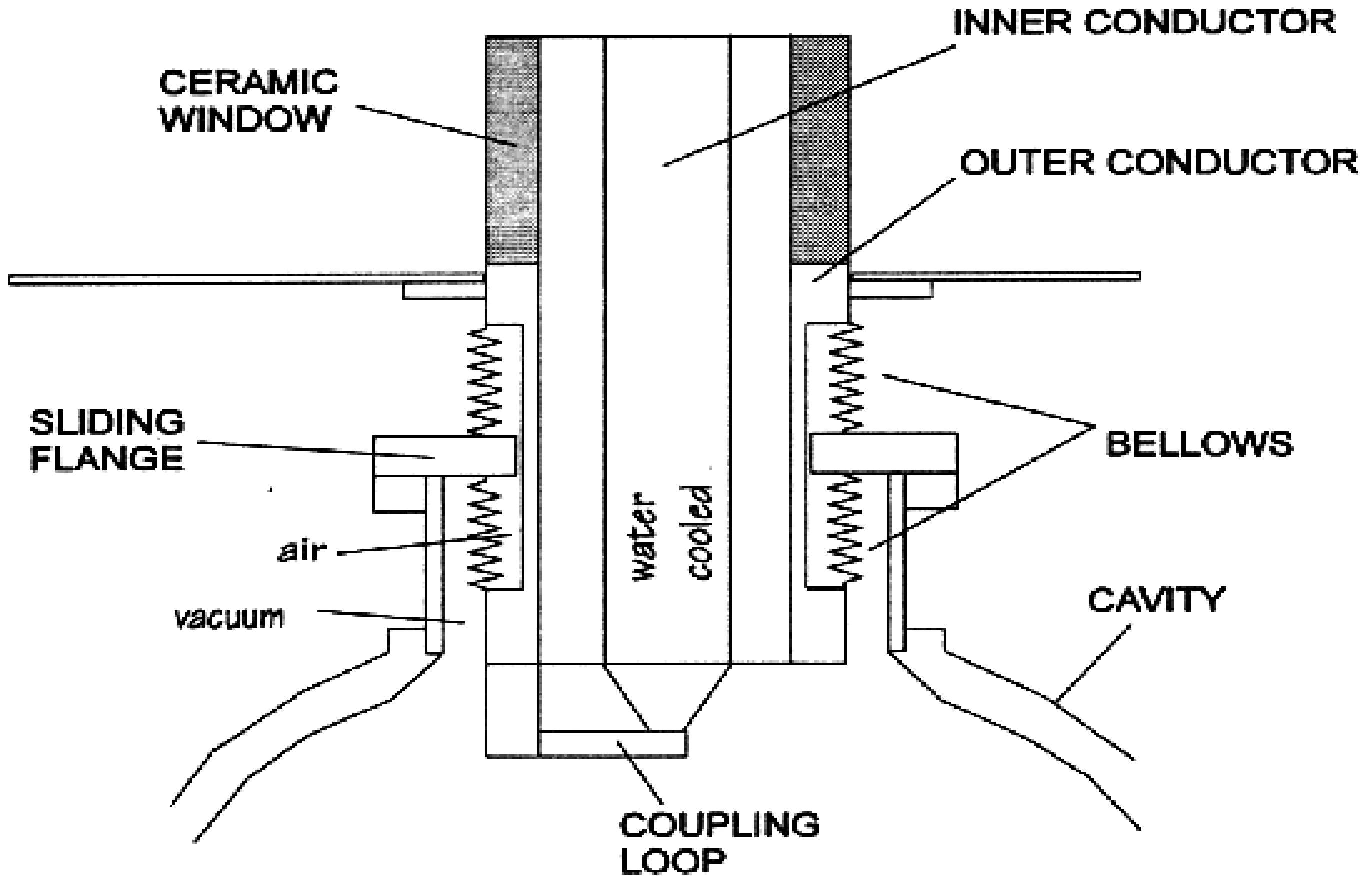
Variable Input Coupler:



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Width of a Resonance

$$P_{total} = -\frac{dU}{dt} \Rightarrow U(t) = U_0 e^{-\omega t/Q_L}$$

U falls to 1/e in a time $\tau = Q_L/\omega$ which can be measured experimentally to give the loaded Q.

For perfectly conducting walls with isolated cavity(no ports) we have an infinite Q_o and the resonances of all modes are thus razor sharp δ-functions.

In a lossy cavity wall losses result in a finite Q_0 and energy transmission through any ports means that $Q_L < Q_0$ which serve to broaden the resonances. Excitation of a mode is hence possible even if the frequency is not tuned perfectly, provided it at least les within the line width of the resonance.

We know that the energy density scales as the electric field squared. We can express the electric field in a loaded cavity as

$$E(t) = E_0 e^{-\omega_0 t/2Q_L} e^{-i(\omega_0 + \Delta\omega)t}$$

Where ω_0 is the resonance frequency of the equivalent perfectly conducting cavity and $\Delta\omega$ is included to allow for a possible (small) frequency shift in the resonance frequency due to any losses. We can determine the electric field as a function of frequency by FT.

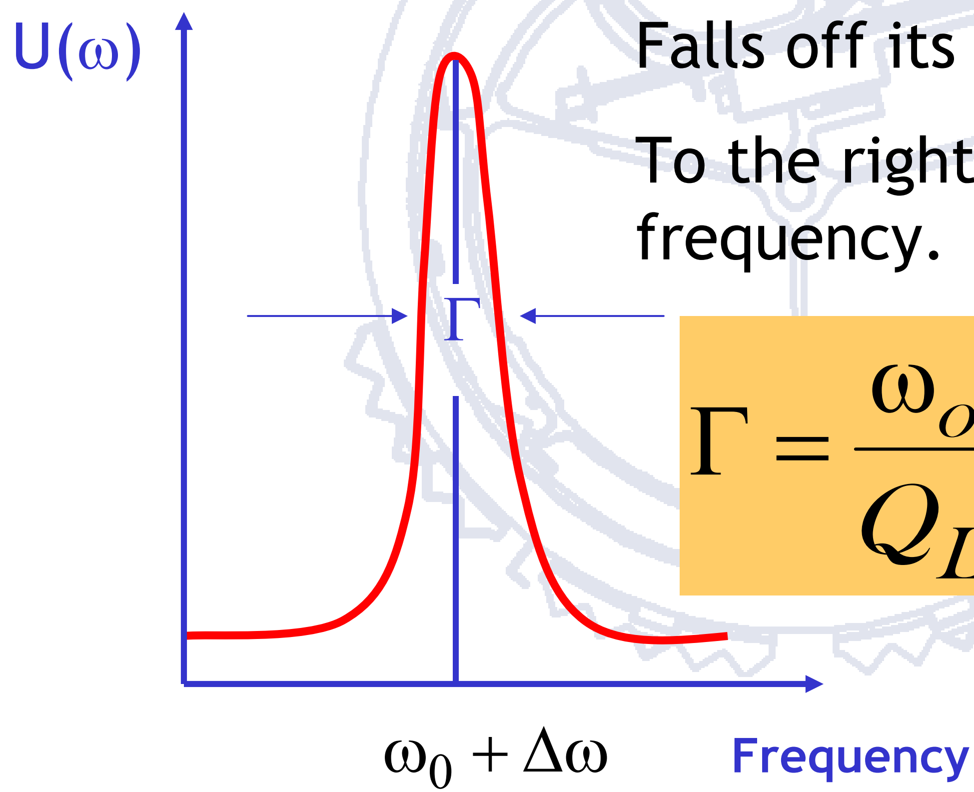
$$E(\omega) = E_0 \int_0^{\infty} e^{-\omega_0 t/2QL} e^{-i(\omega_0 + \Delta\omega)t} dt$$

$$E(\omega) = \frac{E_0}{i(\omega - (\omega_0 + \Delta\omega)) - \omega_0/2Q_0}$$

The energy density per frequency interval scales as:

$$U(\omega) \propto |E(\omega)|^2 \propto \frac{1}{(\omega - \omega_0 - \Delta\omega)^2 + (\omega_0 / 2Q_0)^2}$$

Classical Breit-Wigner shape



Falls off its peak value at $\omega_0 / 2Q_L$

To the right and left of central frequency.

$$\Gamma = \frac{\omega_o}{Q_L}$$

Relationship between Q_L and Q_0

$$Q_e = \frac{\omega U}{P_e} \qquad Q_t = \frac{\omega U}{P_t}$$

From before we had:

$$Q_0 = \frac{\omega U}{P_{diss}} \qquad Q_L = \frac{\omega U}{P_{total}} \qquad P_{total} = P_{diss} + P_e + P_t$$

Input Probe

Output Probe

$$Q_L = \frac{\omega U}{P_{total}} = \frac{\omega U}{P_{diss} + P_e + P_t}$$

$$\boxed{\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_e} + \frac{1}{Q_t}}$$

If we identify the "coupling parameters" as $\beta_e = Q_0/Q_e$ and $\beta_t = Q_0/Q_t$, then

$$\boxed{\frac{1}{Q_L} = \frac{1}{Q_0}\left(1 + \beta_e + \beta_t\right)}$$

If we can determine the coupling parameters and loaded Q, then Q_0 can be calculated.

Using the coupling between the input probe and the cavity and if no output probe is present, then the reflected power is simply give by

$$P_r = \left(\frac{1-\beta_e}{1+\beta_e}\right)^2 P_i$$

Similarly, the instantaneous emitted power is given by

$$P_e = \frac{4\beta_e^2}{(1+\beta_e)^2} P_i$$

Solving these equation we obtain two expressions for β_e:

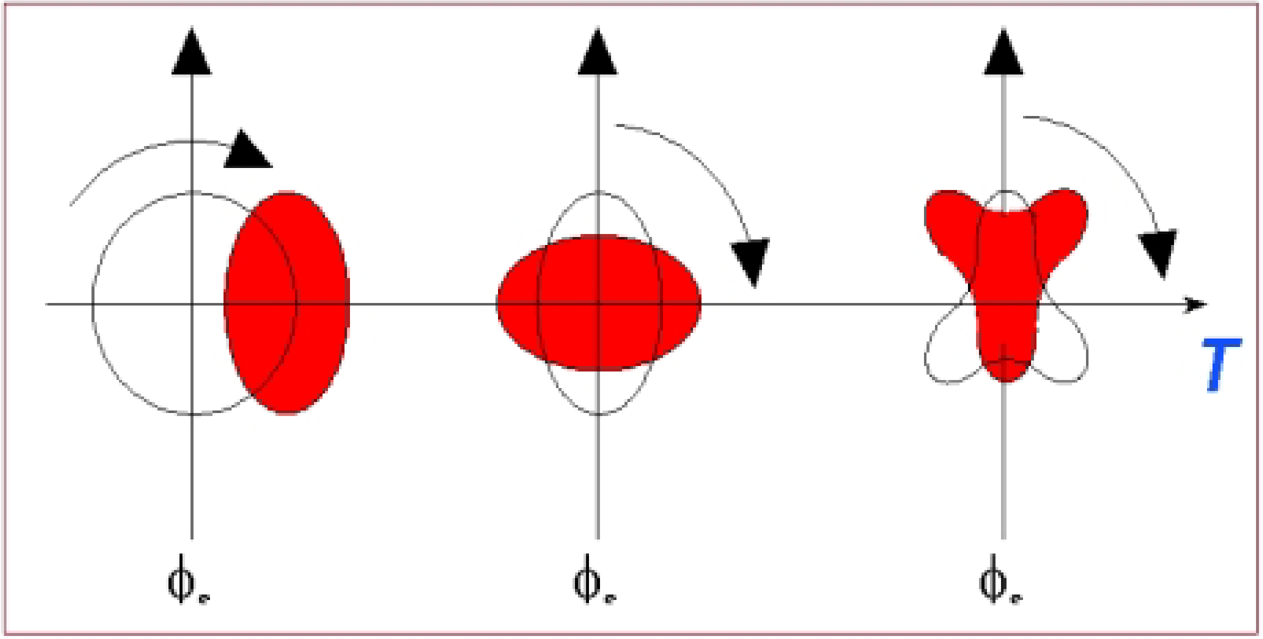
$$\beta_e = \frac{1 \pm \sqrt{\dfrac{P_r}{P_i}}}{1 \mp \sqrt{\dfrac{P_r}{P_i}}} \qquad \beta_e = \frac{1}{2\sqrt{\dfrac{P_i}{P_e}} - 1}$$

Higher Order Modes (HOM)

- Cavity geometry dictates the electromagnetic field distribution.
- Cavity will not only resonate at the desired fundamental frequency but also at other higher order mode frequencies.
- Could be major contributor to coupled bunch beam instability.
- Coupling to the fundamental mode
- Beam induced HOM are the essential driving terms for the excitation of multi bunch oscillations
- Could be major contributor to coupled bunch beam instability.
- This results in the deterioration of photon beam of the undulators leading to emmitance blowup and/or energy spread.
- Reduced photon beam brilliance.

Higher Order Modes (HOM)

Longitudinal Coupled Bunch (LCB) Synchrotron Modes.



a = 1 Dipole

a = 2 Quadrupole

a = 3 Sextupole

Longitudinal Coupled Bunch (LCB)

LCB Growth Rate

$$\Delta w = \frac{eIF_0}{4E_0}\frac{\alpha F_i R_i F_m}{F_s}$$

E = electron charge

I = beam current (mA)

F_e= Orbit frequency (Hz)

α=Momentum compaction

F_i = Resonant frequency (Hz)

R_i = Longitudinal impedance Ω

E_0 = Beam energy (eV)

F_s = Synchrotron frequency (Hz)

F_m = Bunch shape factor

Longitudinal Coupled Bunch (LCB)

LCB Threshold Current

$$I_s = \frac{2E_0\nu_s}{\tau_s\alpha}\frac{1}{F_i R_i}$$

E_0 = Beam energy (eV)

ν_s =Synchrotron Tune

τ_s = Radiation Damping Time

F_i = Resonant frequency (Hz)

R_i = Longitudinal impedance (Ω)

Transverse Coupled Bunch (TCB)

- Similar rigid oscillations to dipole LCB except in the transverse plane (a=0).

- a=1 mode implies that the bunch head and tail oscillate transversely out of phase.

Transverse Coupled Bunch (TCB)

TCB Growth Rate

$$\Delta w = \frac{\beta I F_0}{2E_0} R_i F_m$$

β = Vert/Horz beta value at the cavity

I = beam current (mA)

F_0= Orbit frequency (Hz)

R_i = Longitudinal impedance (Ω)

E_0 = Beam energy (eV)

F_m - Bunch shape factor

HOM

- Cavity HOM's are problems at certain beam current and fill patterns.

- Avoiding HOM!
  - HOM dampers
  - Offset input port
  - Cavity operating temperature

Coupled Bunch Mode

If all electron beam bunches are uniformly filled in a storage ring, i.e. identical current in every bunch, and the beam exhibits no coherent oscillation, the beam spectra will contain components *n* of Bf_{rev}, where B is the number of bunches and f_{rev} is the revolution frequency. Peaks at other frequencies indicate a non-uniform fill or that the beam exhibits some coherent oscillation. Providing the bunches move in a correlated way, the beam spectrum contains components:

$$f^{\pm}_{\mu,n} = nBf_{rev} \pm \left(\mu f_{rev} + f_s\right)$$

μ is the mode number of the coupled bunch oscillation

f_s is the synchrotron frequency

Coupled Bunch Mode

In circular accelerators, the electromagnetic field generated by the bunched beam, the wake field, interacts with the surrounding and, under certain circumstances, can be amplified and can act back on subsequent bunches. Disturbances grow and so-called collective beam instabilities arise. The machine environment is seen by the bunch as a frequency dependent impedance, that can be sampled by the beam spectral components.

A single bunch beam usually performs small oscillations along the unperturbed single particle orbit, or stationary trajectory. Therefore at a fixed location along the machine, the signal of a single bunch has the frequency components :

$$f_{mp} = pf_0 + mf_0$$

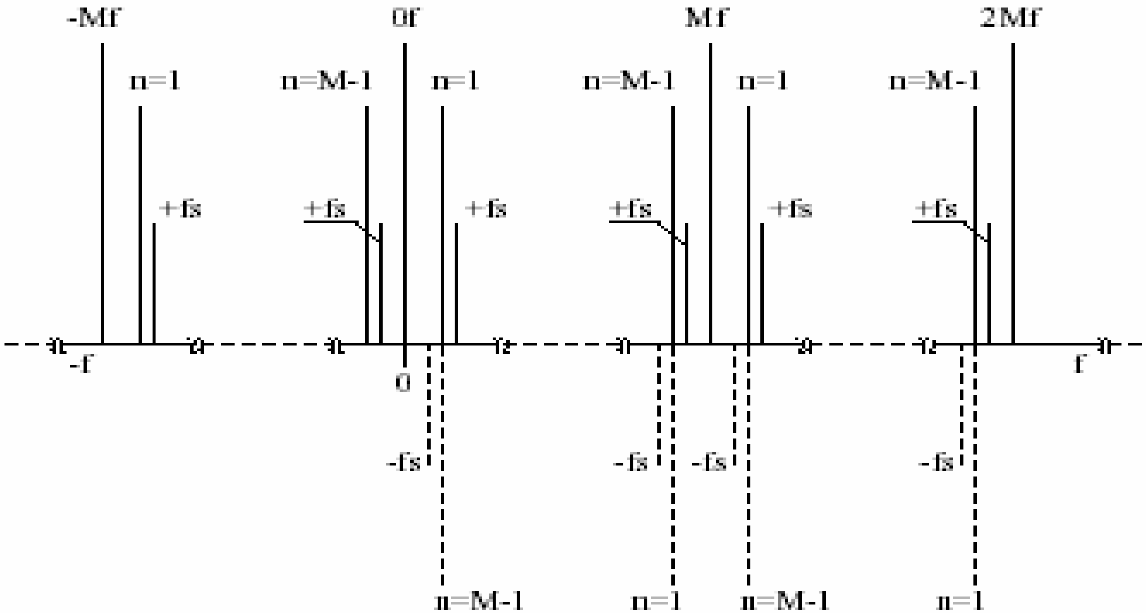
f_0 is the revolution frequency, p is an integer, $-\infty<p<+\infty$, number of beam turns. The index m is the single bunch mode oscillation, m=0 is a stationary bunch, m=1 is oscillation of a dipole mode (rigid bunch), m=2 is a quadrupole mode, etc.

Coupled Bunch Mode

If the ring is filled with *M* uniform equally spaced bunches, the motion of each bunch can coupled together in *M* different modes of oscillations:

$$f_{m,n,p} = pMf_0 + nf_0 + mf_s$$

where n= 0, ... , M-1 indicates the n^{th} Coupled Bunch oscillation Mode (CBM).

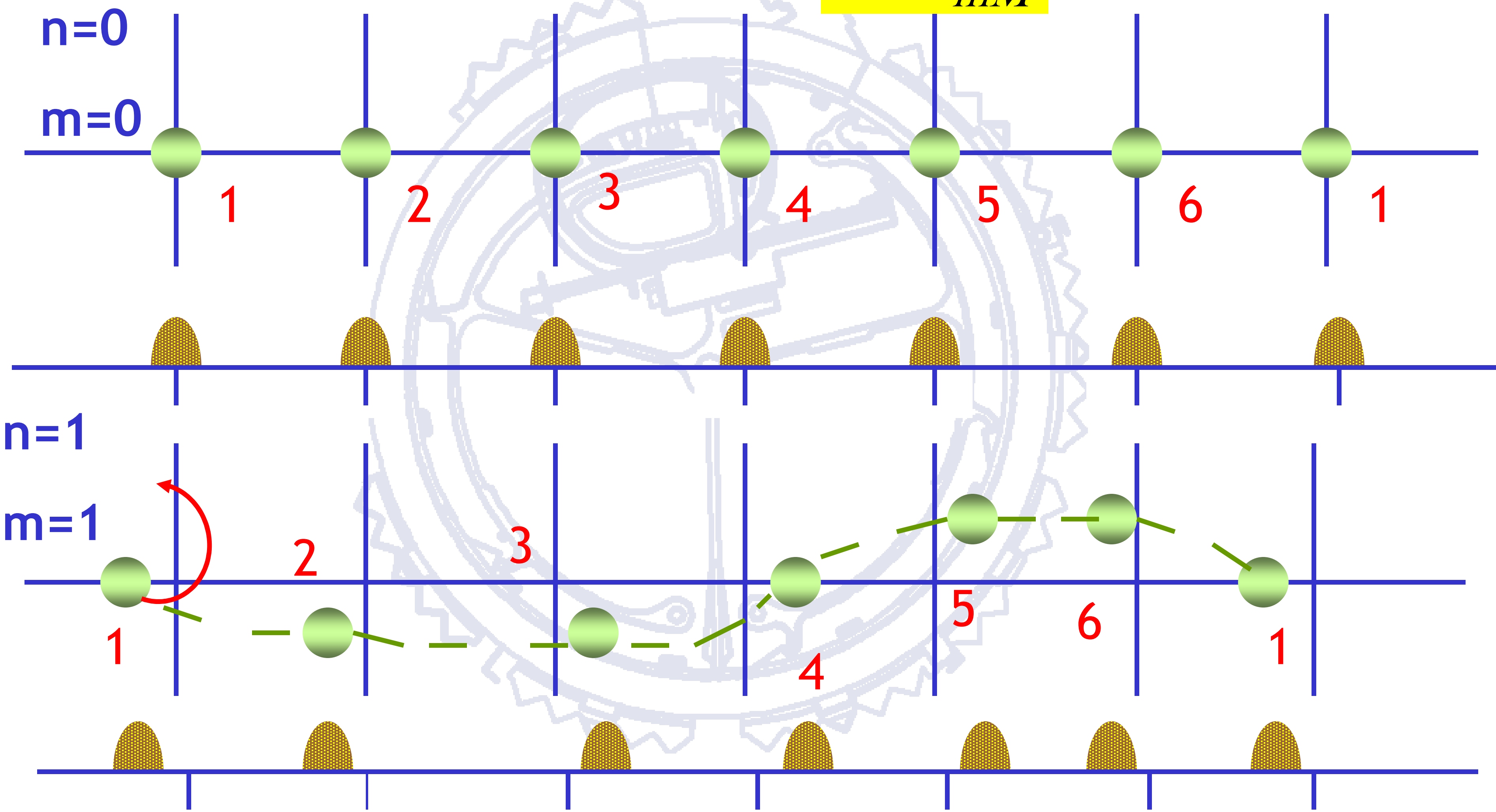


Sketch of the frequency lines for the p=-1,0,+1 values. The pattern repeats running from -∞ to +∞. Dashed lines represent the frequency lines p=-1 aliased in the positive range, p=1.

Coupled Bunch Mode

Example: Six bunches, M=6

$$\theta_{nm} = \frac{2\pi n}{mM}$$



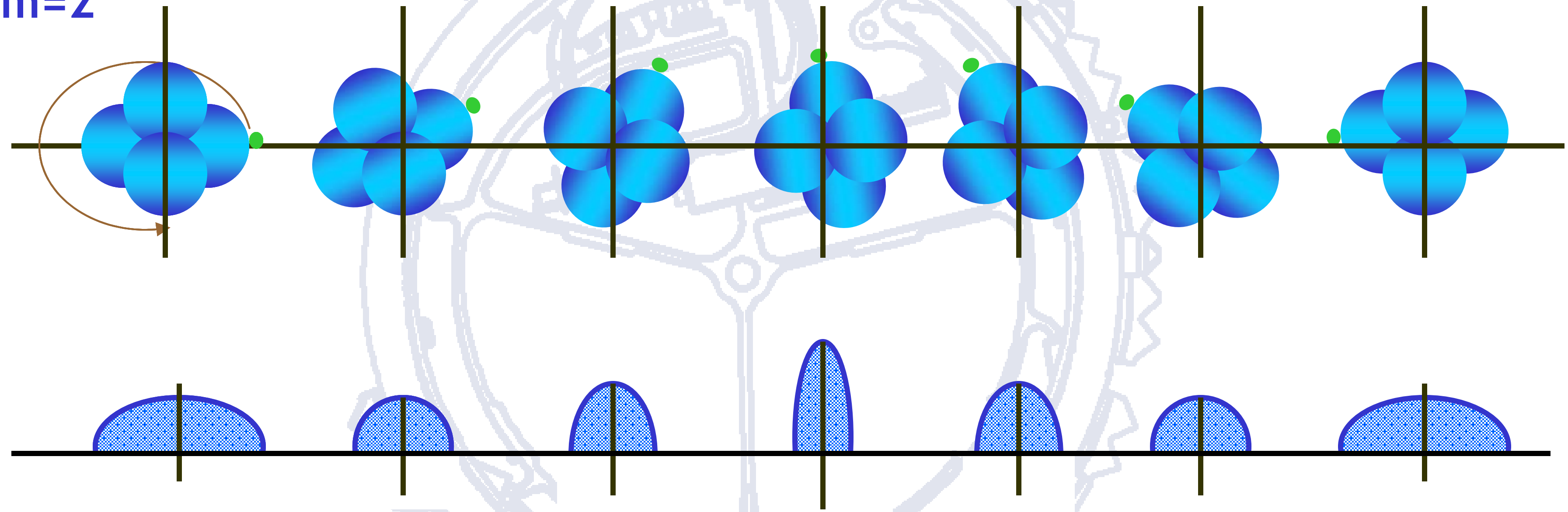
Coupled Bunch Mode

Example: Six bunches, M=6

$$\theta_{nm} = \frac{2\pi n}{mM}$$

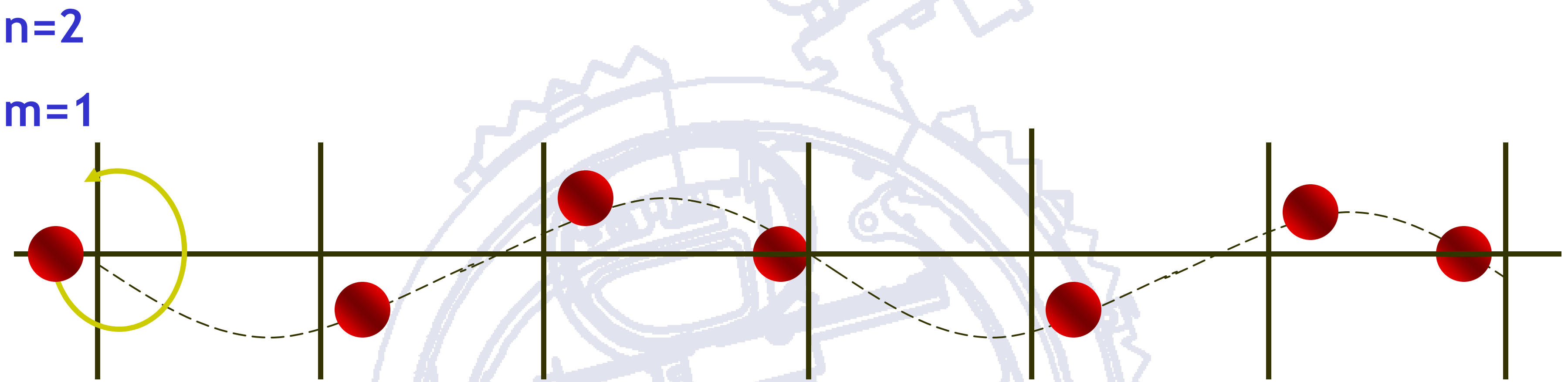
n=1

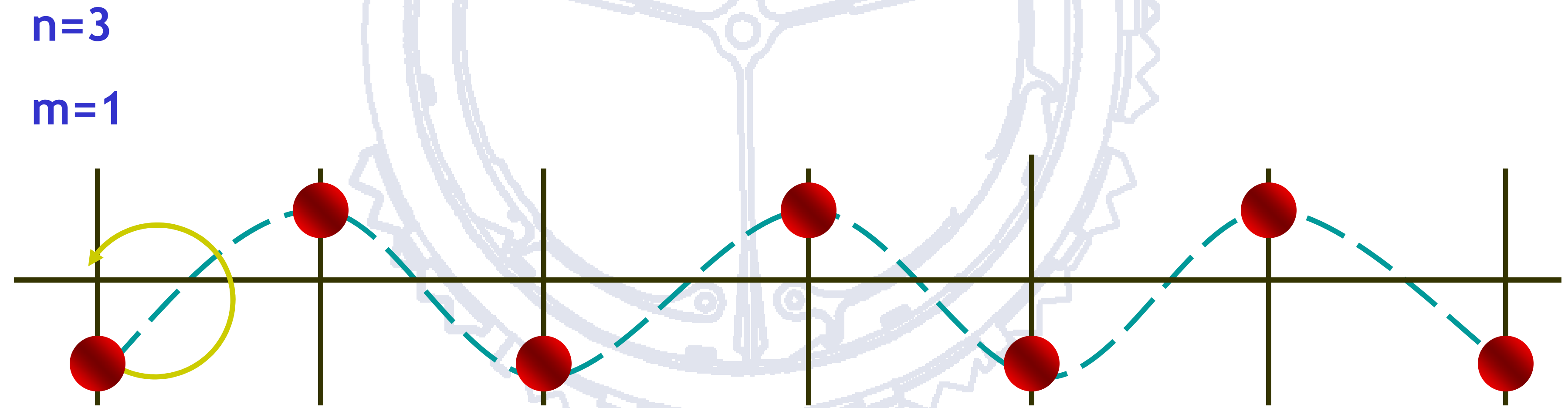
m=2



Phase oscillation representation for n=1 Coupled-Bunch Quadrupole Mode m=2.

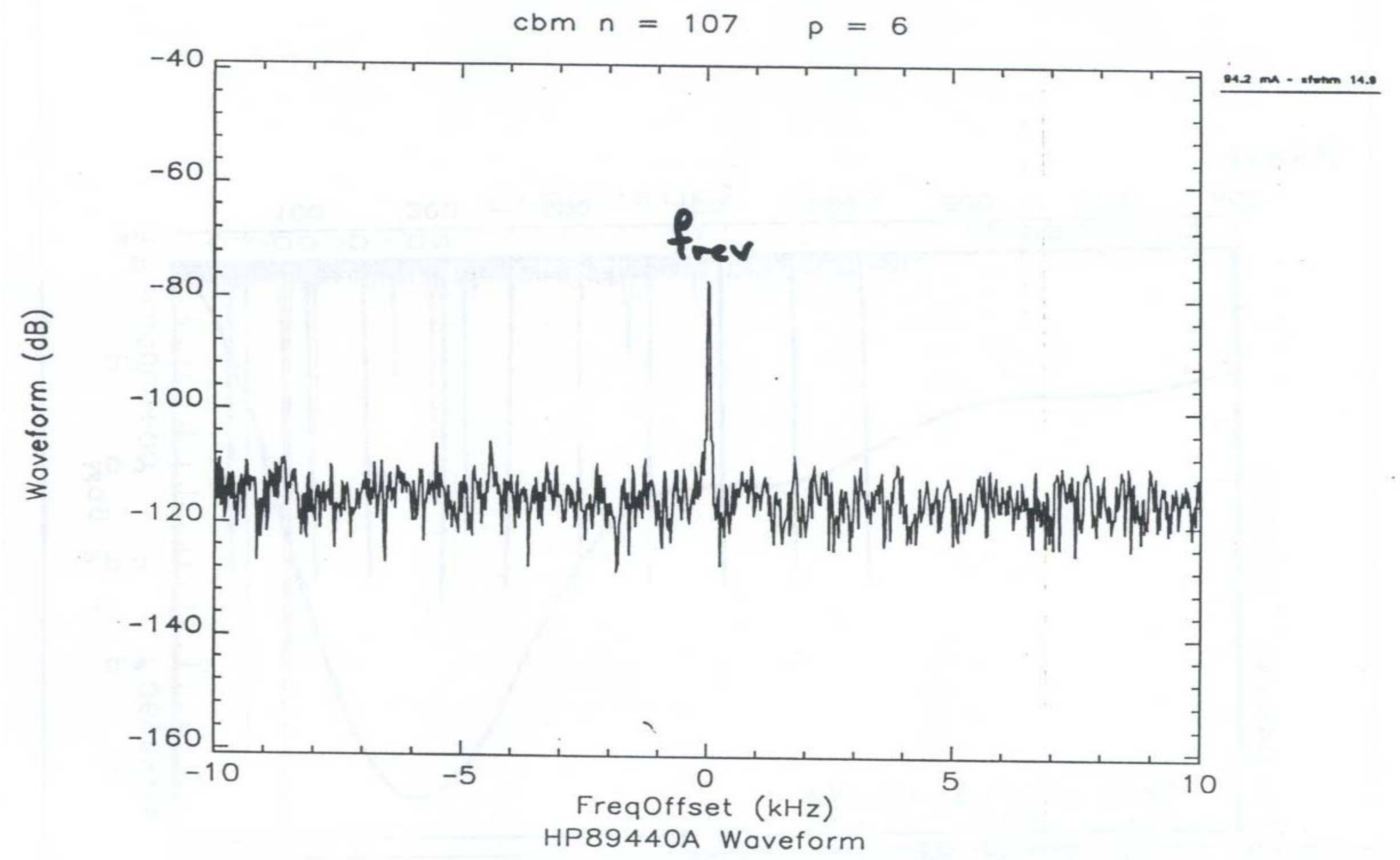
Coupled Bunch Mode





Coupled Bunch Mode

Stable



f center @ 2140.62 MHz

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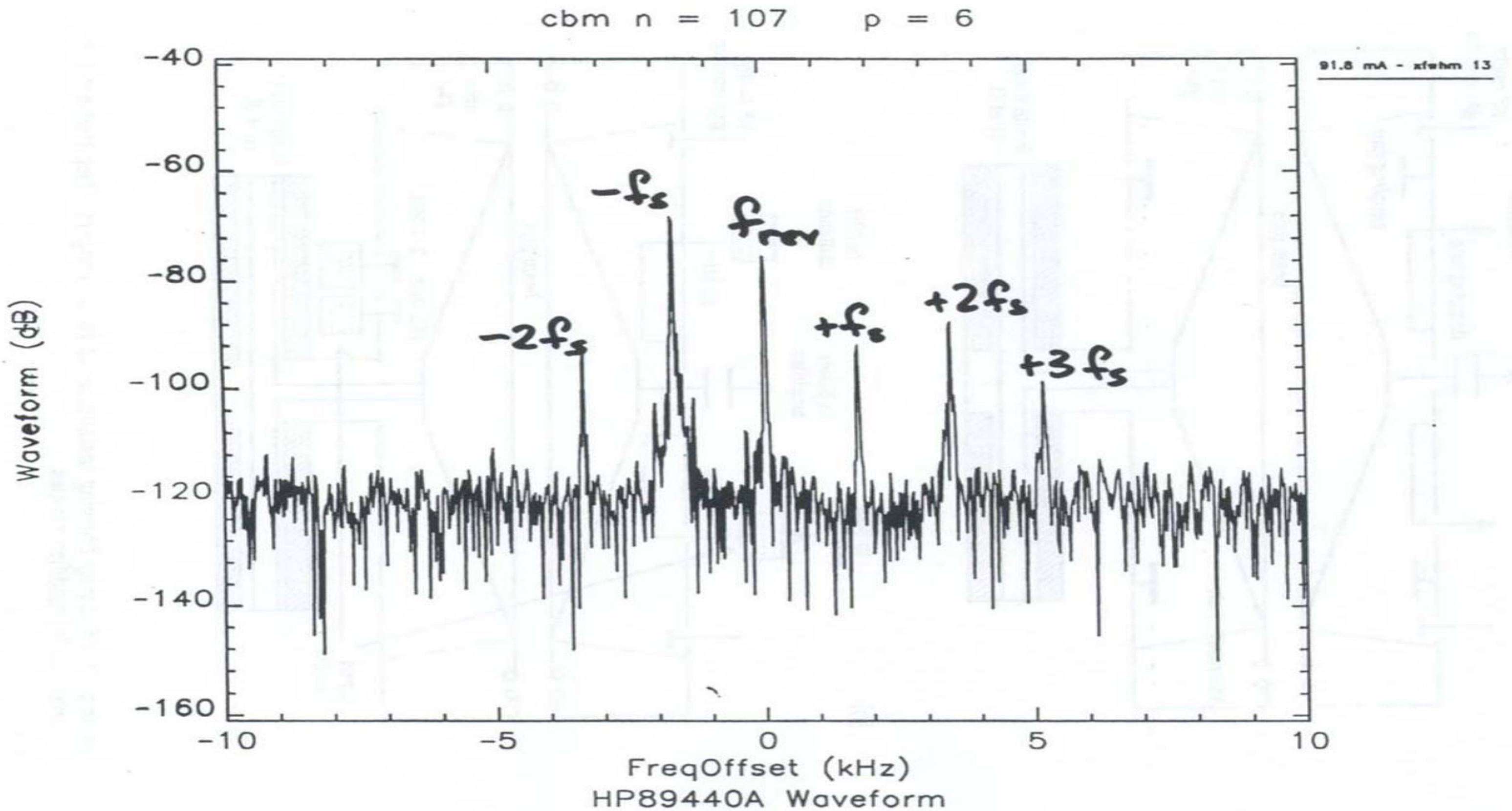
Coupled Bunch Mode

Unstable



f center @ 2140.62 MHz

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Coupled Bunch Mode

Estimated synchrotron frequency spread for 6+200 fill, from simulation

(per C. Schwartz, A. Nassiri, Y. Kang, R.L. Kustom, proc. PAC97)

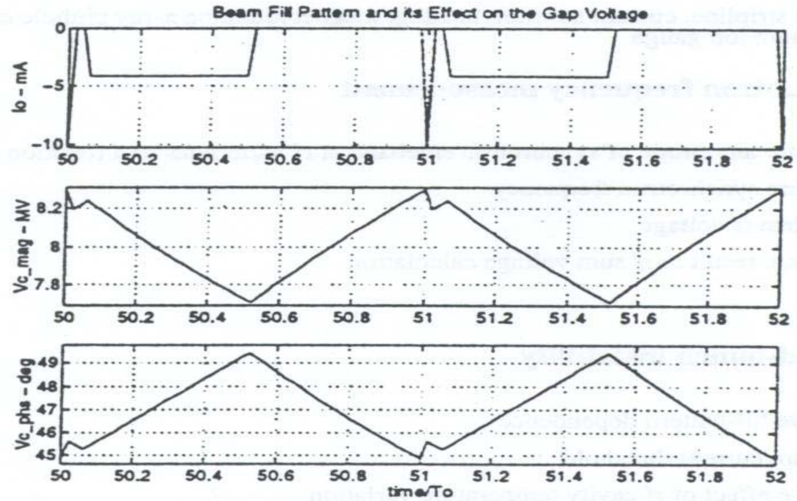


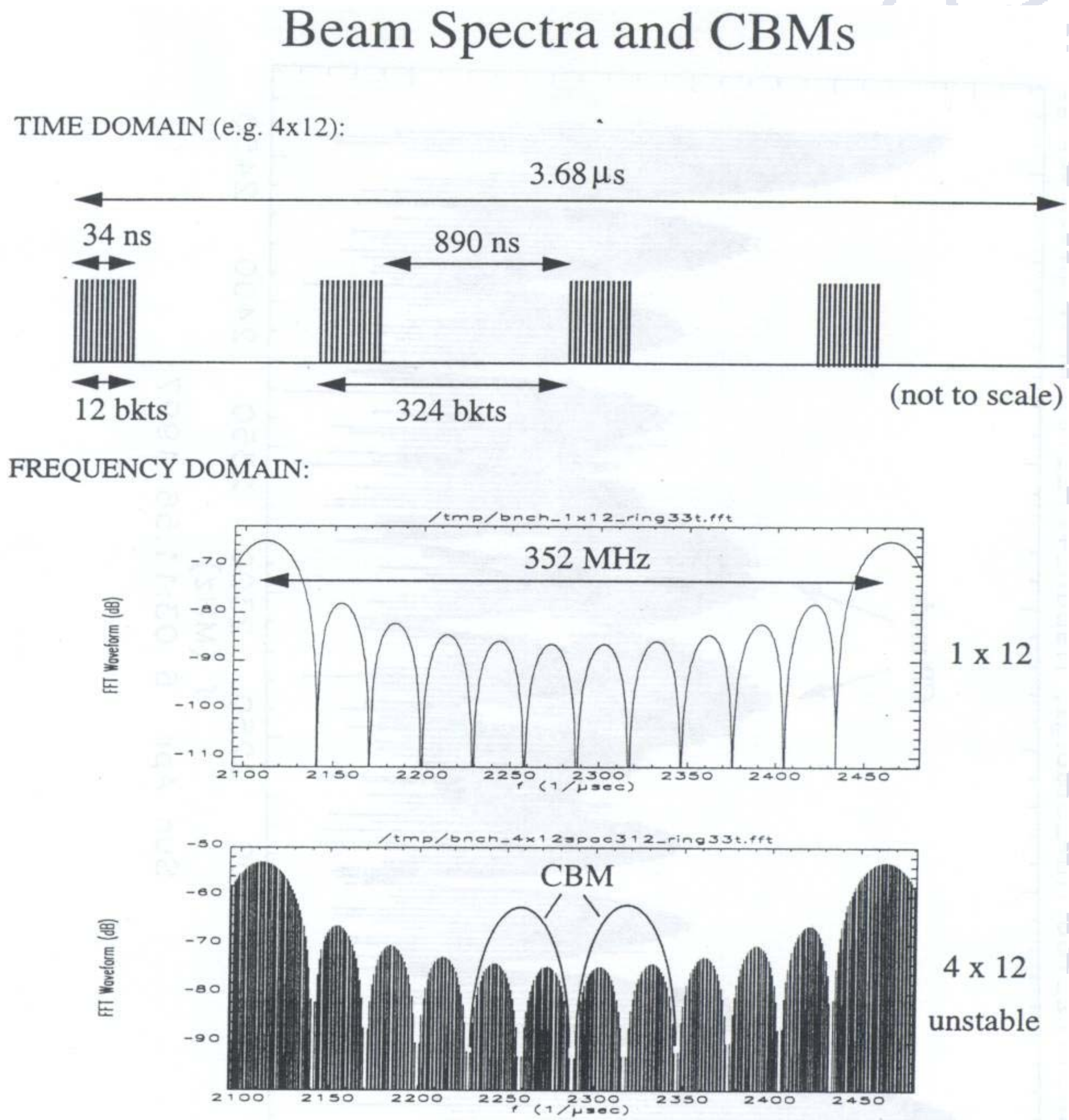
Figure 3: The asymmetric gapped fill pattern, shown over two revolutions (a), induces AM and PM modulations of the cavity gap-voltage shown in (b) and (c), respectively. The nominal cavity set points are 8.0 MV and 47.1°.

8.2 MV, fs = 1.74 kHz

7.7 MV, fs = 1.64 kHz

Δfs = 100 Hz

Coupled Bunch Mode



- Number of peaks in envelope correspond to number of bunches in a train.
- Spacing of the revolution harmonics under envelope (not resolved in the measurements) gives number of trains.
- Power at one of the peaks (or between) indicates a coupled-bunch mode within bunch train.

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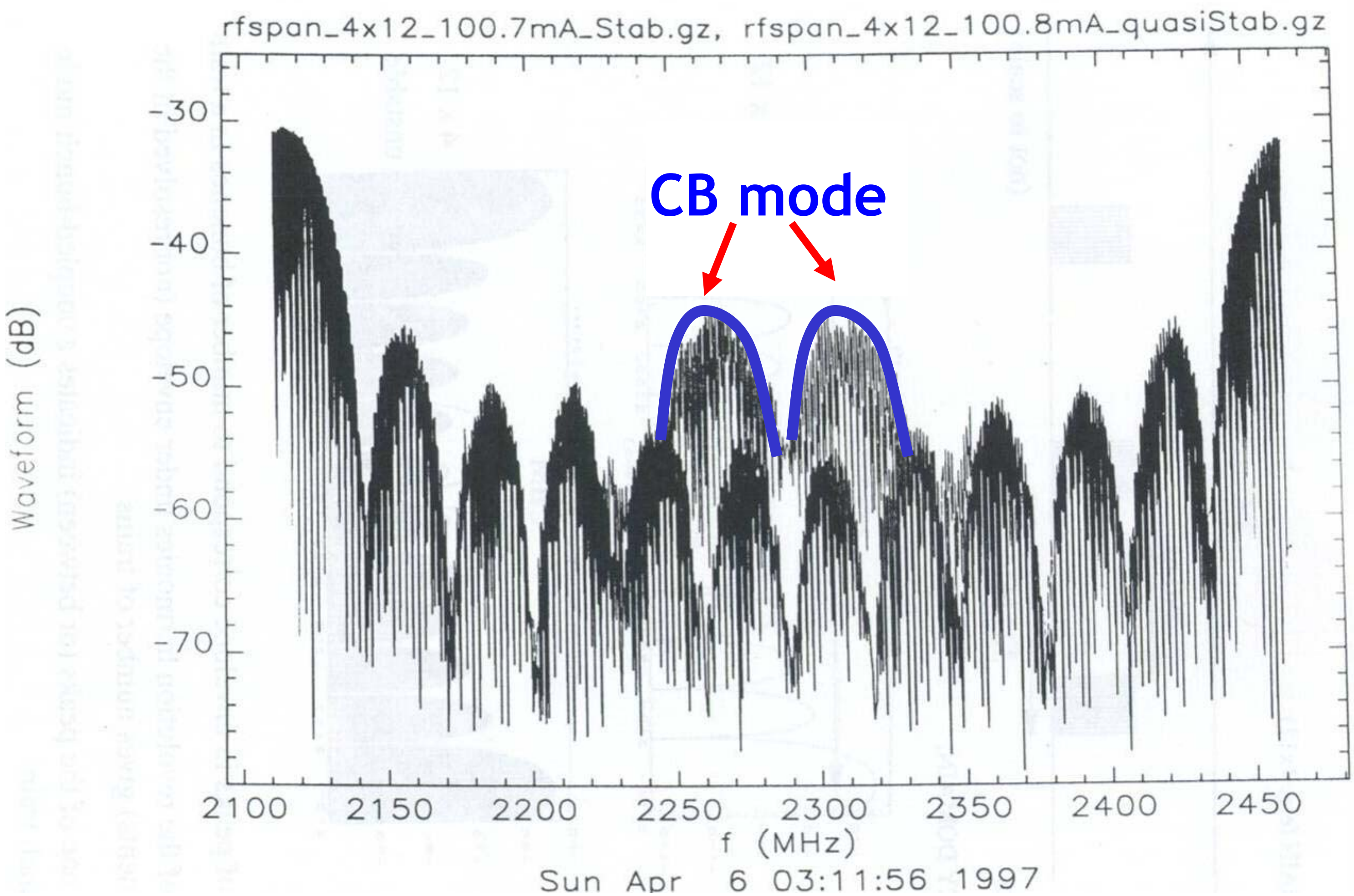
Coupled Bunch Mode

4x12 fill pattern



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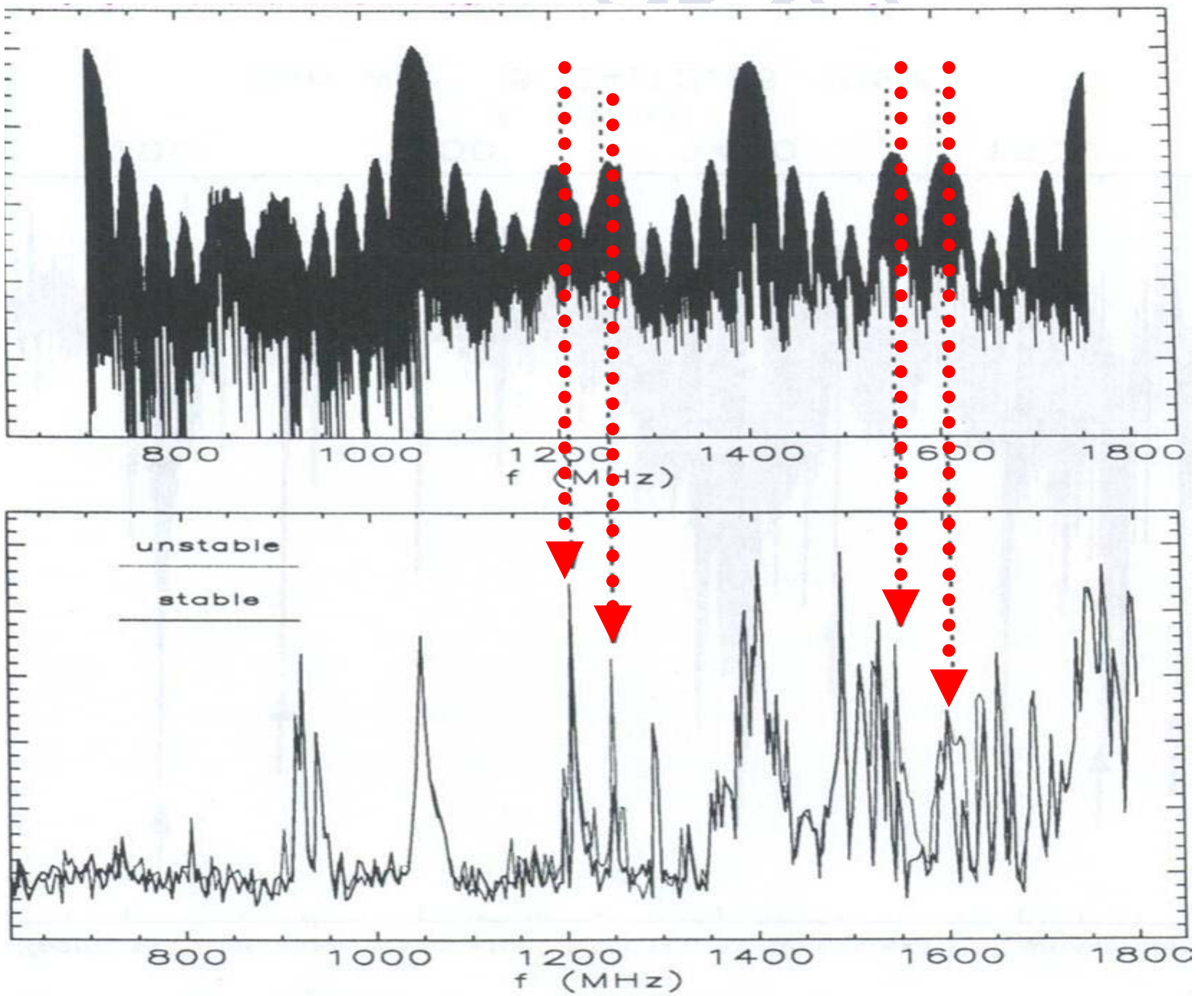
Coupled Bunch Mode

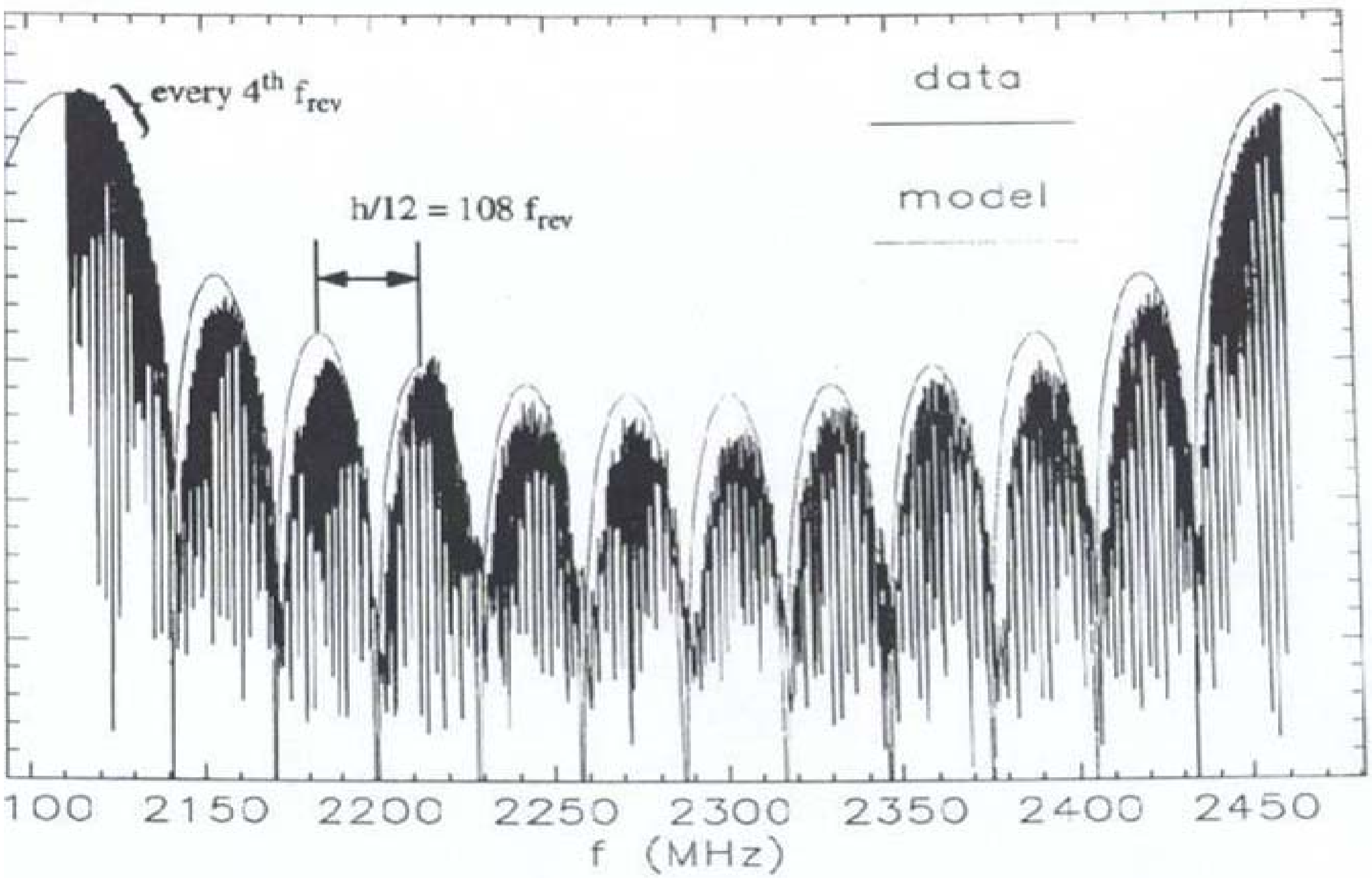


ıstable beam CB spectrum, 4×12 bunch pattern vs. (b) excited HOM spectrum in rf cavity.

Harkay, et. al.

Coupled Bunch Mode

352 MHz



Stable beam spectrum. 4x12 bunch pattern.

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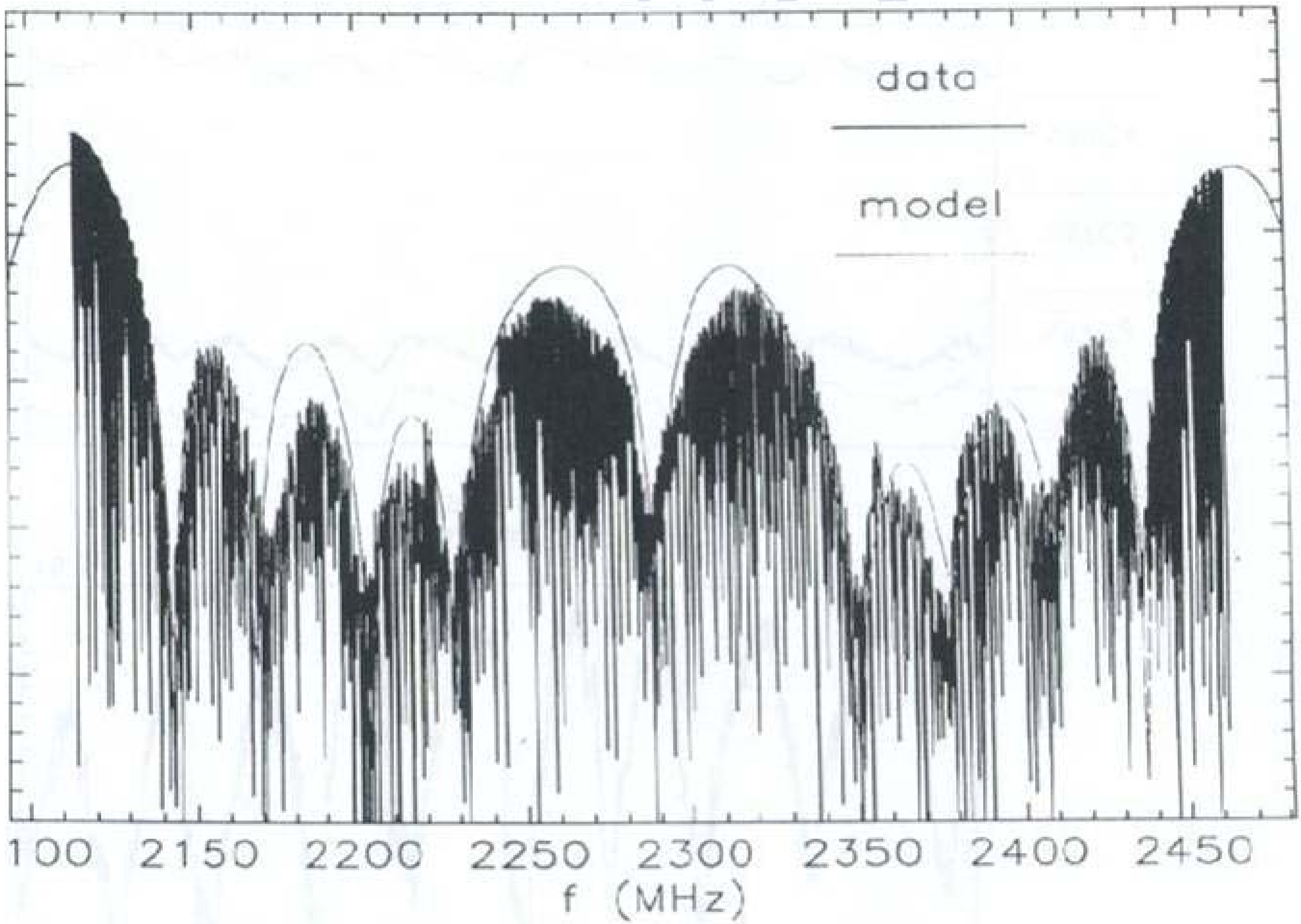
Coupled Bunch Mode



Unstable beam spectrum, 4x12 pattern. An interbunch phase advance corresponding to CBM n=540 introduced in mode, using a max. displacement of 7 degs (55 ps).

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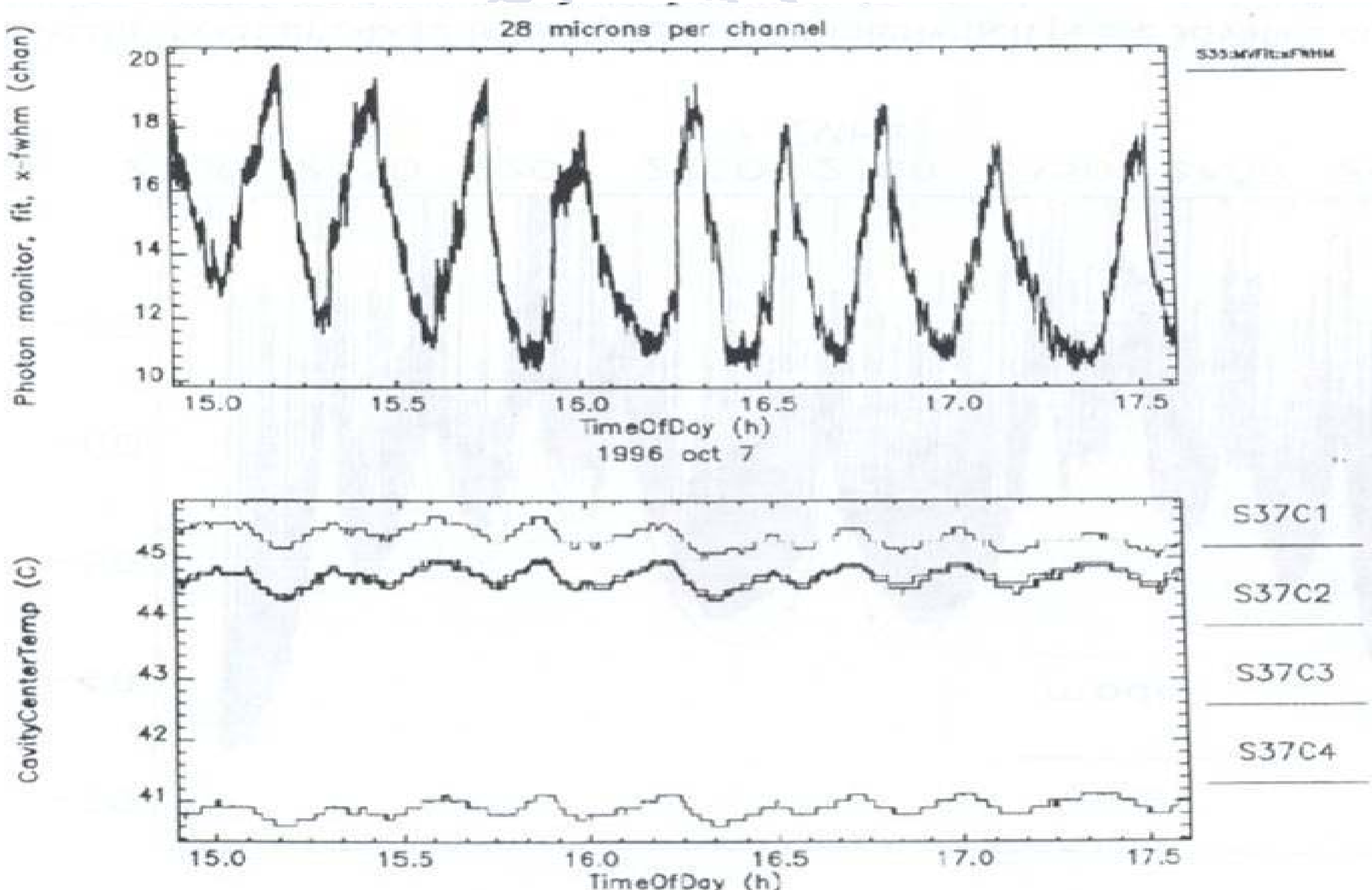
Coupled Bunch Mode

Correlation with S37 cavity temperatures (13-20 min fluctuations)



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